

Environmental life cycle assessment of hybrid steel construction featuring metal additive manufacturing

Jiachi Yang*, Kyvelou Pinelopi, M. Ahmer Wadee and Leroy Gardner

Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK

ARTICLE INFO

Keywords:

DED-arc additive manufacturing
Embodied carbon
Global warming potential
Hybrid manufacturing
Life cycle assessment
Steel beams

ABSTRACT

Hybrid manufacturing, featuring the addition of steel material onto hot-rolled structural steel members through direct energy deposition arc (DED-arc) – a type of metal additive manufacturing (AM) – has recently been demonstrated as a viable means to produce hybrid steel members with considerably enhanced structural performance and material efficiency. The enhanced performance stems from the optimised deposition location and/or the high strength of the DED-arc additions. This underscores its potential for reducing both the material consumption and the environmental impacts of steel construction, thereby improving overall sustainability. In the present study, the environmental impacts associated with the production of hybrid DED-arc-hot-rolled steel I-section beams are investigated through a cradle-to-gate life cycle assessment (LCA), with beams making up approximately 70% of the mass of typical building structures. A unit-mass analysis was first conducted whereby unit mass (i.e., 1 kg) productions of hot-rolled and DED-arc steels were examined. The results of this unit-mass analysis were then used to evaluate the environmental impacts of a series of hybrid beam specimens investigated in previous experimental studies. Finally, a comprehensive parametric study, covering a wide range of I-section profiles and steel beam design scenarios, is presented. The findings demonstrate that the hybrid DED-arc-hot-rolling manufacturing strategy is capable of reducing the overall embodied carbon associated with steel beams by, on average, 11% and 14% for normal and high strength steel additions to S355 steel profiles, and up to approximately 40%, for some typical loading conditions. For S275 steel profiles, which are likely to feature prominently in retrofitting and re-use scenarios, the savings in embodied carbon are even greater, up to 45%.

1. Introduction

As of 2025, the buildings and construction sector accounts for some 34% of the global energy-related CO₂ emissions, up from 29% in 2015 [1]. This shows that the construction sector is still not on track to reduce 28% of the global CO₂ emissions by 2030, as required under the Paris Agreement on tackling climate change [2], and to achieve net-zero emissions by 2050 [3–5]. Construction materials such as steel and cement are identified as major sources of CO₂ emissions, accounting for approximately 18% of global building-related CO₂ emissions. This highlights the urgent need for sustainable structural design and construction methodologies that consume less material and improve material efficiency.

Directed energy deposition arc (DED-arc) is a type of metal additive manufacturing (AM) that is capable of achieving high deposition rates and producing metal parts with complex geometries [6, 7]. Previous research has examined the mechanical performance of DED-arc material [8–12] and has demonstrated the use of DED-arc in producing structural steel components with high material efficiency, offered by structural optimisation and/or a new hybrid manufacturing strategy [13–20], with some examples shown in Fig. 1. The hybrid manufacturing strategy, featuring depositing steel material onto conventional hot-rolled steel members through DED-arc, offers a new paradigm for producing steel members with considerably enhanced structural performance, particularly when the DED-arc steel additions are

*Corresponding author

 jiachi.yang20@imperial.ac.uk (J. Yang)
ORCID(s): 0009-0004-4442-6406 (J. Yang)

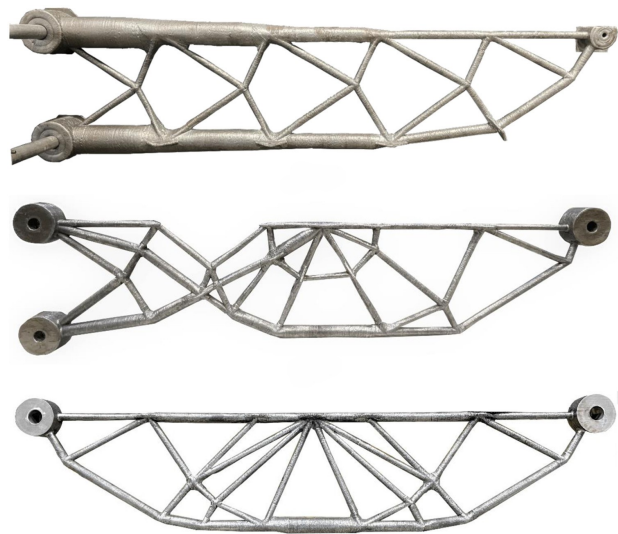
carefully designed and deposited in optimised patterns [21]. For instance, Yang *et al.* [18, 19] investigated the structural response of a series of hybrid DED-arc-hot-rolled steel I-section beams through physical experiments. The results of these experimental studies showed that disproportionate increases in the ultimate bending moment resistance of between 40% and 80% were achievable for the hybrid beam specimens with increases in mass (i.e., from the DED-arc steel additions) of between just 5% and 15%, resulting in considerably higher overall material efficiency compared to conventional hot-rolled I-section beams. This indicates the potential of this hybrid manufacturing strategy in reducing the material consumption and, consequently, the carbon footprint of structural steel beams.



(a)



(b)



(c)



(d)

Figure 1: Some optimised DED-arc structural steel components and hybrid DED-arc-hot-rolled steel members: (a) MX3D Takenaka node [22], (b) optimised garden bridge [13], (c) optimised steel trusses [16] and (d) hybrid DED-arc-hot-rolled I-section steel column [17].

Environmental life cycle assessment (LCA) is a useful tool for evaluating the carbon footprint/ CO_2 emissions and other environmental impacts, such as water depletion, arising from engineering products. International standards – ISO 14040 [23], ISO 14044 [24] – have been established providing guidance and frameworks for the implementation of LCA. In the last few years, a sizeable body of LCA work has emerged for additively manufactured (AM) metal parts [25–29]. Kokare *et al.* [30] conducted a systematic review of LCA for metal AM, mostly in aviation, aerospace

and biomechanical applications, with 82% of the reviewed studies showing less CO₂ emissions from the AM products compared to their conventionally manufactured counterparts. Additionally, a few studies were conducted comparing the carbon footprints of structural steel materials or members, fabricated through DED-arc, with those of conventional counterparts manufactured through hot-rolling or cold-forming [31, 32]. However, these studies adopted either a geometrically equivalent or a mass-equivalent basis for comparisons, rather than using a functionally equivalent basis that is more suitable in the context of structural engineering. Shah et al. [33] conducted a comparative LCA for DED-arc structural steel members on a functionally equivalent basis in terms of the load carrying capacity, which is the first of its kind, where the carbon footprints of a conventional hot-rolled steel I-section beam and of a topologically optimised DED-arc beam – see Fig. 1(c) – with 53% less weight but the same load carrying capacity, were evaluated and compared. The results of this study showed that a mass saving of around 50% is required for DED-arc steel members to achieve favourable CO₂ emissions at typical deposition rates, highlighting the critical role of structural optimisation in designing and fabricating sustainable DED-arc steel members.

The present study extends this design-oriented LCA approach focusing on structural (functional) equivalency reported by Shah et al. [33] to the aforementioned hybrid DED-arc-hot-rolled steel I-section beams. Unlike fully additively manufactured members, hybrid beams retain a conventional hot-rolled steel section as the main load-carrying component and use DED-arc steel additions only in targeted regions to enhance structural efficiency. In this study, a comprehensive parametric design framework is established to compare the environmental impacts of hybrid and conventional hot-rolled beams on a functionally equivalent, design-code-oriented basis, which is the first of its kind. In this framework, the conventional hot-rolled beam is selected to provide at least the same design bending resistance as its hybrid counterpart (i.e., functionally equivalent), enabling the environmental benefits of hybrid manufacturing to be evaluated in direct relation to structural design requirements.

The environmental impacts of the hybrid DED-arc-hot-rolled steel I-section beams investigated in [18, 19] have yet to be examined; this, therefore, forms the scope of the present study. A brief review of the hybrid beam testing [18, 19] is presented in Section 2. In Section 3, the environmental impacts associated with the unit-mass (i.e., 1 kg) production of hot-rolled and DED-arc steels are evaluated through a cradle-to-gate LCA, which is referred to as a unit-mass analysis. The results of this unit-mass analysis are then used in Section 4 to examine the environmental impacts of the hybrid beam specimens summarised in Section 2. Finally, a comprehensive parametric study, covering a wide range of I-section profiles and steel beam design scenarios, is conducted in Section 5 to assess the overall influence of this hybrid manufacturing strategy on the carbon footprint of steel beam design, where it is demonstrated that a reduction in the carbon footprint of up to 40% is achievable for some typical loading conditions. The key findings are summarised and conclusions are drawn in Section 6.

2. Review of previous experiments

This section provides a brief summary of the previous experimental investigations on hybrid DED-arc-hot-rolled steel I-section beams conducted by Yang *et al.* [18, 19]. The results of these studies are then used in the life cycle impact assessments presented in the subsequent sections.

In [18, 19], the major-axis flexural behaviour of a series of hybrid DED-arc-hot-rolled steel I-section specimens was assessed through physical testing under either a four-point bending or a three-point bending condition. In the hybrid beam specimens, normal-strength steel additions (i.e., fabricated using ER70S-2 unalloyed welding wire) or high-strength steel additions (i.e., fabricated using ER110S-G or ER120S-G low-alloyed welding wire) were deposited onto hot-rolled bare I-sections in grade S355 steel through DED-arc. A schematic illustration for these hybrid beam specimens is presented in Fig. 2, featuring DED-arc steel additions deposited at the compression flange tips in the form of stiffeners, and at the outer surface of the tension flange. The layout of the DED-arc steel was designed and optimised based on the bending moment diagram resulting from the applied load(s). Essentially, a moment resistance diagram, established as the major-axis plastic bending moment resistances, $M_{pl,y}$, of the cross-sections along the length of the hybrid beam, is optimised to match the bending moment diagram within the DED-arc-deposited regions closely, see Fig. 3, thereby resulting in a more uniform utilisation along the length of the beam and improving material efficiency.

LCA – hybrid DED-arc-hot-rolled steel beams

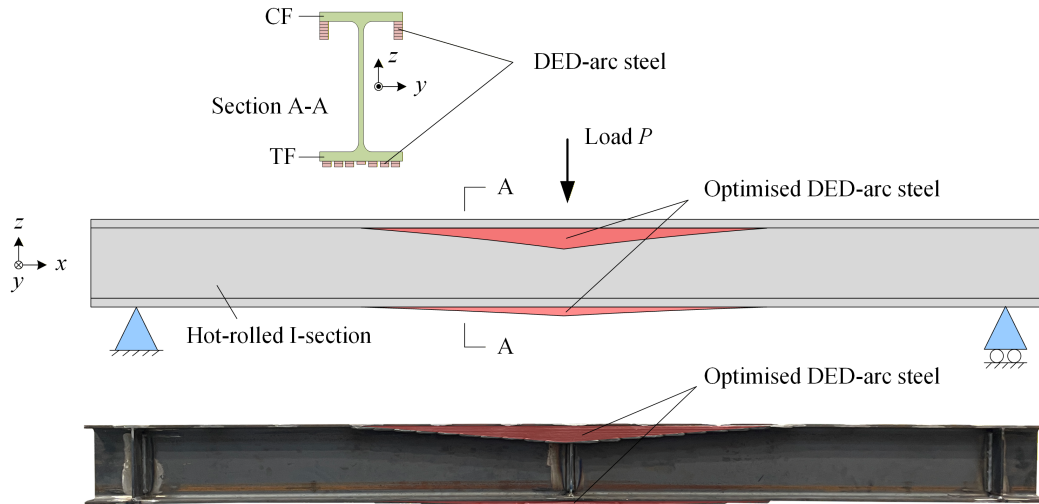


Figure 2: Illustration of hybrid DED-arc-hot-rolled steel I-section beam [18, 19] (CF – compression flange, TF – tension flange).

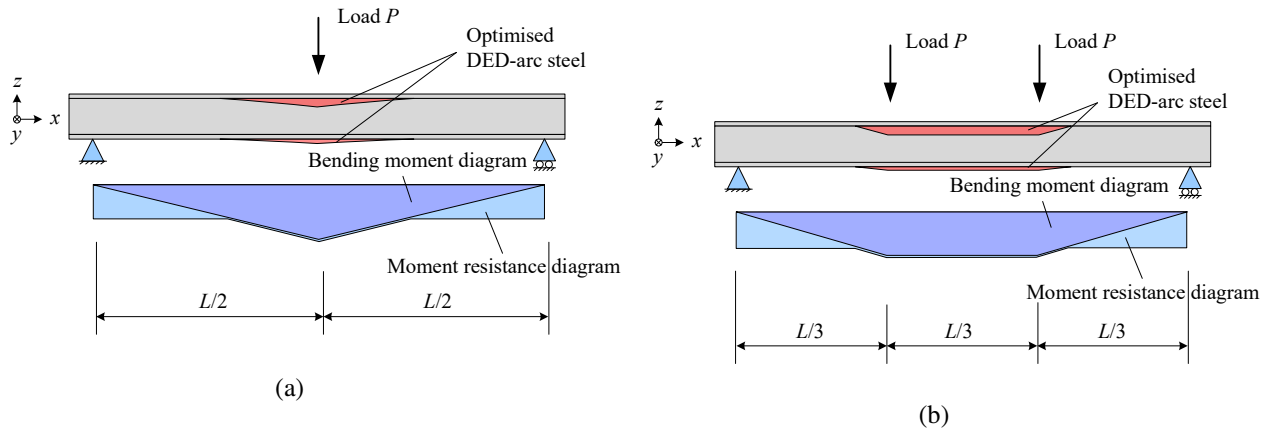
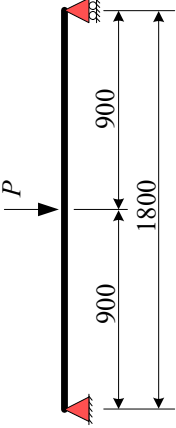
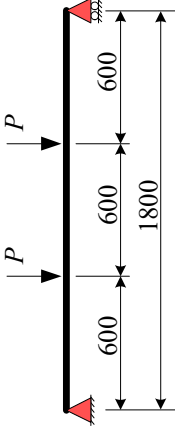


Figure 3: Optimisation for the layout of DED-arc steel additions based on the applied bending moment diagram: (a) under three-point bending (3PB) and (b) under four-point bending (4PB).

The information of some typical hybrid beam specimens is briefly summarised in Table 1, while full details of these specimens can be found in [18, 19]. For comparison purposes, a series of bare I-section beams was also tested in [18, 19] as a benchmark; information regarding these benchmark specimens is also provided in Table 1.

Table 1: Information of some typical beam specimens investigated in [18, 19] (3PB – three point bending, 4PB – four point bending, * – benchmark specimens, unit for dimension: mm).

Loading condition	Specimen-ID	I-section profile	m_l (kg)	m_w (kg)	m (kg)	$\frac{m_l}{m_w}$	M_{Rd} (kNm)	M_u (kNm)	$\frac{M_{Rd}}{M_{u,b}}$	$\frac{M_u}{M_{u,b}}$
Three-point bending 	*ER70-3PB-0%	UB 152×89×16	28.40	0.00	28.40	0.00%	49.43	67.36	1	1
	*ER110/120-3PB-0%	IPE160	28.96	0.00	28.96	0.00%	51.92	66.85	1	1
	ER70-3PB-10%	UB 152×89×16	28.81	3.18	31.99	11.04%	68.96	84.75	1.40	1.26
	ER110-3PB-5%	IPE160	29.13	1.64	30.77	5.63%	76.13	87.88	1.54	1.30
	ER110-3PB-10%		28.92	3.10	32.02	10.72%	86.52	104.60	1.75	1.55
	ER110-3PB-15%		28.82	4.46	33.28	15.48%	98.49	114.12	1.99	1.69
	ER120-3PB-5%		29.22	1.61	30.83	5.51%	75.35	96.23	1.52	1.43
	ER120-3PB-10%		28.73	2.97	31.70	10.34%	84.33	106.26	1.71	1.58
Four-point bending 	ER120-3PB-15%	UB 152×89×16	28.92	4.45	33.37	15.39%	96.80	123.12	1.96	1.83
	*ER70-4PB-0%	UB 152×89×16	28.70	0.00	28.70	0.00%	50.02	56.70	1	1
	*ER110/120-4PB-0%	IPE160	28.68	0.00	28.68	0.00%	51.17	54.38	1	1
	ER70-4PB-10%	UB 152×89×16	28.89	3.37	32.26	11.66%	61.99	75.53	1.24	1.33
	ER110-4PB-5%	IPE160	28.73	1.67	30.40	5.81%	62.17	73.18	1.24	1.29
	ER110-4PB-10%		29.10	3.19	32.29	10.96%	72.18	86.79	1.44	1.53
	ER110-4PB-15%		28.70	4.42	33.12	15.40%	79.22	92.01	1.58	1.62
	ER120-4PB-5%		28.66	1.73	30.39	6.04%	63.56	77.45	1.27	1.37
	ER120-4PB-10%	IPE160	28.50	3.34	31.84	11.72%	72.39	87.80	1.45	1.55
	ER120-4PB-15%		28.73	4.34	33.07	15.11%	81.36	97.39	1.63	1.72

In Table 1, m , m_I and m_W are the total mass, the mass of the base I-section and the mass of the DED-arc (welded) steel additions, respectively; m_W/m_I quantifies the percentage increase in mass relative to the base I-section; M_u is the ultimate bending moment resistance of the tested beam specimens; M_{Rd} is the design bending moment resistances of the beam specimens, determined in compliance with EN 1993-1-1 [34]. In addition, $M_{Rd,b}$ and $M_{u,b}$ are the ultimate and design bending moment resistance of the corresponding benchmark specimen. For Class-1 cross-sections subjected to major-axis bending, such as the benchmark I-sections in Table 1, M_{Rd} is determined as the plastic bending moment resistance $M_{pl,y}$ of the I-section, as per EN 1993-1-1 [34]. Similarly, for the hybrid specimens with non-uniform cross-sections, the value of M_{Rd} is taken as the plastic bending moment resistance $M_{pl,y}$ of the mid-span cross-section, calculated from the full-plastic cross-sectional stress distribution, as shown in Fig. 4. The yield strengths of the S355 hot-rolled steel and the ER70S-2, ER110S-G and ER120S-G DED-arc steels, used in the calculation of M_{Rd} , were taken as 410 MPa, 375 MPa, 590 MPa and 645 MPa respectively, for consistency with the material testing results reported in [18, 19].

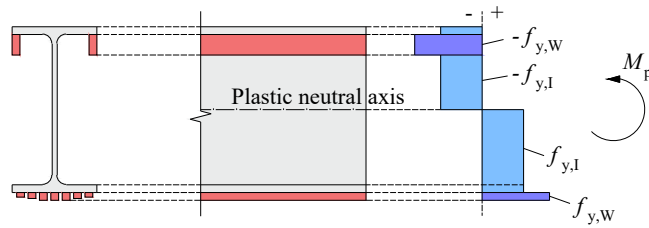


Figure 4: Cross-sectional stress distribution for the calculation of $M_{pl,y}$ of hybrid beams, where $f_{y,W}$ and $f_{y,I}$ are the yield strengths of the DED-arc (welded) steel and of the hot-rolled steel within the I-section, respectively.

The specimens are labelled using the convention – ‘welding wire grade – loading condition – approximate percentage mass increase’. For instance, ER110-3PB-15% refers to a hybrid specimen with ER110S-G DED-arc steel additions and an approximately 15% percentage mass increase, tested under three-point bending (3PB). Similarly, ER110/120-3PB-0% denotes the benchmark specimen corresponding to all the ER110/120-3PB hybrid beams.

It should be mentioned that, for the remainder of the current paper, all the structural properties and responses of steel beams are evaluated and referred to with respect to major-axis bending only, unless specified otherwise. Consideration of minor-axis bending and lateral torsional buckling [35] are beyond the scope of the present study.

3. Unit-mass analysis

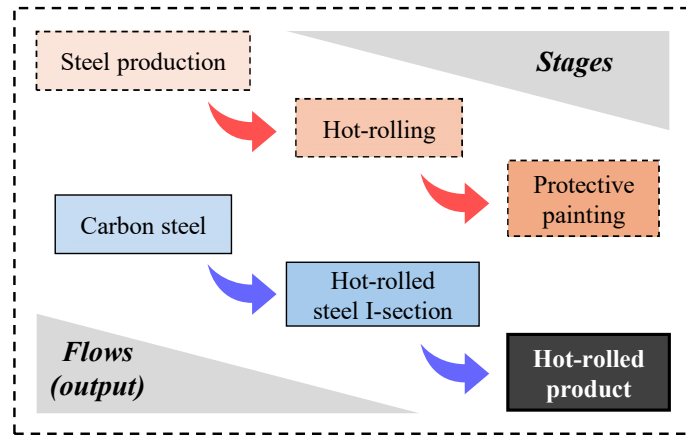
In the current section, a cradle-to-gate LCA was conducted using the OpenLCA package [36] and the *Ecoinvent* 3.8 database [37] is presented. The purpose of the LCA is to investigate the environmental impacts associated with producing a unit mass of: (a) hot-rolled steel I-section in grade S355, (b) normal-strength DED-arc steel manufactured using ER70S-2 welding wire, (c) high-strength DED-arc steel manufactured using ER110S-G welding wire, and (d) high-strength DED-arc steel manufactured using ER120S-G welding wire. The production stages and system boundaries employed in the LCA, the life cycle inventory (LCI) and the modelling approaches are described herein.

3.1. Production stages and system boundaries

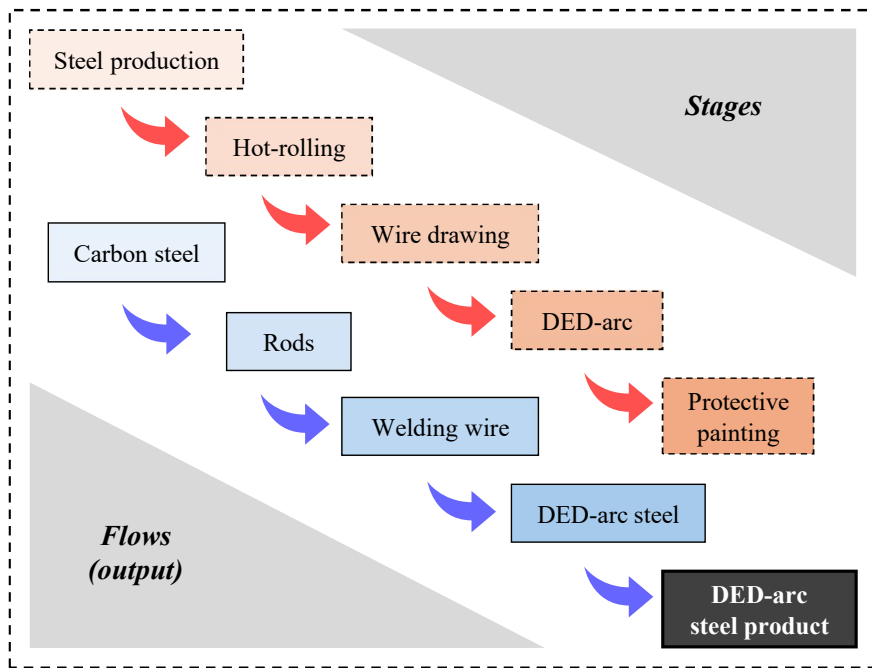
In the present study, three production stages are considered for the hot-rolled S355 steel I-section: (i) the production of normal-strength carbon steel blooms, (ii) the hot-rolling process that rolls the steel blooms into hot-rolled I-sections, and (iii) the protective painting process yielding the final coated product ready for delivery to end users. For the DED-arc steels, five production stages are included: (i) the production of normal-strength or high-strength carbon steel billets/ingots, (ii) the hot-rolling process that produces steel rods, (iii) the wire drawing process converting steel rods into welding wire consumables, (iv) DED-arc manufacturing, and (v) protective painting.

A cradle-to-gate system boundary is adopted herein, encompassing the extraction, transportation and processing of raw materials, and the subsequent manufacturing and fabrication processes within the factory. However, activities beyond the factory gate, such as the transportation of products to the end users, the use, maintenance and end-of-life

treatment of the products, are excluded from this system boundary. The production stages, system boundaries, and the corresponding flows/outputs of each production stage, are illustrated in Figs. 5(a) and (b) for the hot-rolled S355 I-section and the DED-arc steels respectively.



(a)



(b)

Figure 5: System boundaries and production stages for (a) S355 hot-rolled I-section production and (b) DED-arc steel production (dash line boxes indicate production stages, while solid line boxes represent the corresponding flows).

It should be noted that, in the remainder of this paper, ‘S355/ER70S-2/ER110S-G/ER120S-G steel production’ refers specifically to the production of the corresponding steel used for subsequent profile rolling or welding wire production. In contrast, ‘Hot-rolled S355 I-section production’ and ‘ER70S-2/ER110S-G/ER120S-G DED-arc steel production’ denote the complete production chains of the respective final steel products.

The cradle-to-gate system boundary adopted herein was chosen to focus specifically on the environmental implications associated with the production activities of the hybrid manufacturing strategy examined in this study. Here, “hybrid manufacturing” refers to the production of new structural members by combining conventional hot-rolled steel sections

with DED-arc steel additions. This boundary enables a direct comparison between conventional hot-rolled beams and hybrid DED-arc-hot-rolled beams on a functionally equivalent basis.

It should be noted that the DED-arc additive manufacturing technology can also be used for retrofitting or strengthening existing structural members; however, analysing the environmental impacts of such applications would require a different LCA framework. The retrofitting or strengthening forms part of the maintenance and life-extension of existing structures, rather than the production of a new structural component, which renders a cradle-to-gate boundary unviable. Instead, the environmental impacts of DED-arc retrofitting should be compared with those of alternative retrofitting strategies, member replacement, or no-intervention scenarios over an appropriate cradle-to-grave system boundary. Such assessments are beyond the scope of the present work and will form future research.

3.2. Production of hot-rolled S355 steel I-section

In typical steel production, iron ore is reduced to molten iron in a blast furnace, after which impurities are oxidised and alloying elements are added in a basic oxygen converter to produce crude steel [38, 39]. The molten steel is then continuously cast into slabs, blooms or billets, which can be further hot-rolled and, where required, heat-treated to achieve the desired section geometry and mechanical properties. For the S355 hot-rolled steel I-section, the steel production process was modelled using the reference process '*market for steel, low-alloyed*' from the *Ecoinvent 3.8* database [37], which closely represents the chemical composition and the production route of typical S355 structural steel. Hot-rolling was modelled with the reference process '*market for hot rolling, steel*'. The surfaces of the hot-rolled steel products are often coated with protective paints before use to prevent corrosion and enhance durability. Commonly used protective paints for steel include epoxy paints, alkyd paints, zinc-rich paints, etc [40]. Here, the protective painting was modelled using the '*market for alkyd paint, white, without water, in 60% solution state*' reference process.

3.3. Production of DED-arc steel

As illustrated in Fig. 5(b), the production of DED-arc steel also commences from steel production. However, none of the reference processes for steel production available in the *Ecoinvent 3.8* database [37] closely represents the chemical composition of ER70S-2, ER110S-G or ER120S-G welding wire, particularly the latter two high-strength grades. Therefore, the steel production was modelled using the reference process '*market for steel, unalloyed*' as a basis, which contains no additional alloying elements except carbon, and other alloying elements were then manually added according to the chemical composition provided in respective wire specifications given by the suppliers, as shown in Table 2. For instance, 1 kg of ER110S-G welding wire contains approximately 1.85 wt.% of nickel, thus accordingly, 0.074 kg of ferronickel, with a Ni content of 25%, was added in addition to the unalloyed steel using the '*market for ferronickel*' reference process. Other alloying elements, such as Mn, Cr, Mo and Si etc., were modelled in a similar fashion. The corresponding input flows and reference processes used to model each alloying element are provided in Tables A1–A3; see Appendix A, in which mass conservation is imposed.

The produced steel is then hot-rolled into rods and subsequently drawn into 1.2 mm diameter welding wire. The wire drawing process involves pulling hot-rolled steel rods through a series of progressively smaller dies to reduce their diameter and improve surface finish, dimensional accuracy, and mechanical strength [41]. The hot-rolling process was again modelled with the '*market for hot rolling, steel*' reference process, while the wire drawing was represented by the '*market for wire drawing, steel*' reference process.

The DED-arc steels were deposited using ABB robotic arm systems through metal inert gas (MIG) welding. The process parameters and weld bead geometries for the three grades of DED-arc steel are summarised in Table 3. Note that the same process parameters were applied for the ER110S-G and ER120S-G DED-arc steel. In Table 3, the deposition rate is defined as the mass of the material deposited per hour, without considering the material loss during welding primarily owing to spatter, and the deposition efficiency is defined as the ratio between the mass of the final deposited DED-arc steel and that of the total welding wire consumed (i.e., 1.04 kg of ER110S-G welding wire were consumed to produce 1 kg of ER110S-G DED-arc steel, resulting in a deposition efficiency of 0.96). These ratios were determined experimentally through physical measurements.

Argon (Ar) and carbon dioxide (CO₂) are among the most commonly used shielding gases in MIG welding. Argon, an inert gas, provides a stable arc, smooth metal transfer and minimal oxidation of the weld pool, whereas CO₂, an

Table 2

Typical chemical composition of ER70S-2, ER110S-G and ER120S-G welding wire, provided by the supplier (% by weight, balance Fe).

Element	Composition (wt. %)		
	ER70S-2	ER110S-G	ER120S-G
C	0.05	0.09	0.1
Mn	1.1	1.70	1.8
Si	0.55	0.70	0.8
Cr	–	0.30	0.35
Ni	–	1.85	2.25
Mo	–	0.60	0.6
Al	0.11	–	–
Zr	0.07	–	–

Table 3

Process parameters used for manufacture of ER70S-2, ER110S-G and ER120S-G DED-arc steel.

Process parameters	ER70S-2	ER110S-G & ER120S-G
Wire diameter (mm)	1.2	1.2
Voltage (V)	19.0	18.5
Current (A)	245	165
Power (W)	4655	3052
Travel speed (mm/s)	8	7
Wire feed rate (m/min)	7.4	4.5
Shielding gas	98% Ar, 2% CO ₂	98% Ar, 2% CO ₂
Gas flow rate (l/min)	20	18
Metal transfer mode	Globular transfer	Short-circuiting transfer
Deposition rate (kg/h)	3.92	2.40
Deposition efficiency	92%	96%
Weld bead height (mm)	2.0	1.5
Weld bead width (mm)	8.0	7.5

active gas, enhances arc energy and penetration [42, 43]. Both gases are typically stored in liquid form under controlled temperature and pressure, and are continuously supplied during welding operations through vaporisation. The argon and CO₂ shielding gases were modelled using the ‘market for argon, liquid’ and ‘market for carbon dioxide, liquid’ reference processes, respectively. More specifically, 0.54 kg argon and 0.012 kg CO₂ were assigned per 1 kg of ER70S-2 DED-arc steel, while 0.76 kg argon and 0.018 kg CO₂ were assigned per 1 kg of ER110S-G or ER120S-G DED-arc steel. These shielding-gas consumption values were calculated from the gas flow rate, shielding-gas composition, deposition rate and deposition efficiency given in Table 3, using gas densities of approximately 1.78 kg/m³ for Ar and 1.98 kg/m³ for CO₂ at standard conditions. For each DED-arc steel grade, the deposition time required to produce 1 kg of DED-arc steel, allowing for the deposition efficiency accounting for material loss during deposition, was first determined from the deposition rate. The corresponding total shielding-gas volume was then calculated by multiplying this deposition time by the gas flow rate. This total gas volume was divided into Ar and CO₂ according to the adopted

Table 4

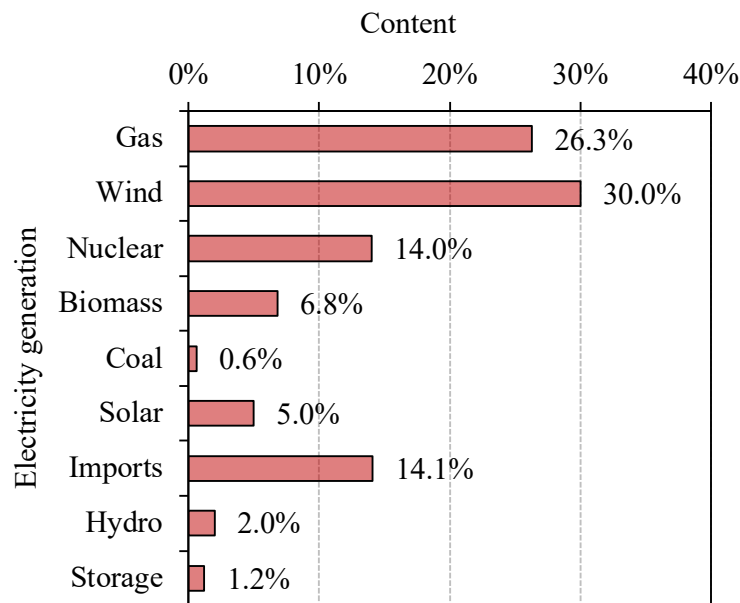
Electricity consumption per 1 kg of DED-arc steel (unit: kWh).

Process	ER70S-2	ER110S-G & ER120S-G
Material deposition	1.291	1.325
Ventilation	0.138	0.225
Robotic movement	0.112	0.183
Sum	1.541	1.733

shielding-gas mixture of 98% Ar and 2% CO₂, respectively, and subsequently converted into mass using the densities of argon and CO₂.

Electricity is the primary energy source for DED-arc, supplying energy for material deposition, ventilation and robotic movement. The energy consumption associated with each of these processes, per 1 kg of manufactured DED-arc steel, is listed in Table 4. The energy required for material deposition was calculated from the welding power and the deposition rate provided in Table 3, allowing for the deposition efficiency. For the ventilation and robotic movement, Bekker and Verlinden [31] reported electricity demands of 0.54 kWh and 0.44 kWh, respectively, for producing 1 kg of DED-arc steel at a deposition rate of 1 kg/h, based on on-site measurements. Using these values as benchmarks, the corresponding energy consumptions for ventilation and robotic movement in the present study – see Table 4 – were determined assuming the values are inversely proportional to the deposition rate.

In modern power systems, electricity is generated through a combination of fossil fuel combustion (e.g., coal, natural gas, oil), nuclear power and renewable sources such as hydropower, wind, solar and biomass. In the present study, the electricity mixture was adopted from the public data provided by the National Energy System Operator (NESO) of the United Kingdom (UK) [44], as shown in Fig. 6. The reference processes used to model these means of electricity production are listed in Table A4 in Appendix A. Additionally, the transmission of electricity from the production sources to the manufacturing site was modelled using the ‘*market for transmission network, electricity, high voltage*’ reference process.

**Figure 6:** Electricity mixture in the UK as of 2024 [44].

Having determined the input flows for the DED-arc process – the welding wire, shielding gases and electricity, the output flows in addition to the DED-arc steel, such as the emissions to the air including carbon dioxide, nitrogen oxides and metal fumes, remained unclear. The values of these emissions were adopted directly from the default ‘*welding, arc, steel*’ reference process [37]. A similar approach was previously employed in [31, 33]. Protective painting was again modelled at the end of the production chain.

3.4. Material utilisation rate

From raw materials to the final hot-rolled I-section or DED-arc steels, materials undergo multiple transformation stages, during which material losses may accumulate. The material utilisation rate is defined as the mass ratio between the downstream output material and its upstream input material. For the steel production, a utilisation rate of 1 was assumed, indicating negligible material loss during forging and continuous casting. In the hot-rolling process, material loss primarily arises from surface oxidation (scale formation), trimming and cutting during shaping and finishing. A utilisation rate of 0.95 was adopted herein, consistent with the default value in the ‘*market for hot rolling, steel*’ reference process [37]. In the wire drawing process, material loss occurs primarily owing to surface descaling and scrapping of the rods. Utilisation rates for wire drawing of 0.85–0.90 and 0.96 are reported by Granta Design [45] and Ecoinvent [37], respectively, and a value of 0.90 was assumed herein. During DED-arc/MIG welding processes, material loss mainly results from spattering, along with the oxidation of molten droplets and partial vaporisation of alloying elements at high temperatures. Material utilisation rates for MIG welding typically range from 0.85 to 0.98, depending on the metal transfer modes [46]. In the present study, rates of 0.92, 0.96 and 0.96 have been adopted for the ER70S-2, ER110S-G and ER120S-G DED-arc steel respectively, as previously given in Table 3 as the deposition efficiency. No material loss is assumed for the protective painting process. The mass of the consumed material(s) at each production stage for finally producing 1 kg of hot-rolled S355 steel I-section or DED-arc steel is summarised in Table A5; see Appendix A.

Having described the life cycle inventories, the modelling procedure and the material utilisation rates, a full model graph is established for the production of a unit-mass of ER110S-G DED-arc steel, as shown in Fig. 7 for illustration purposes.

3.5. Impact assessment

In the present study, the environmental impacts were assessed using the ReCiPe Midpoint (H) method [47], which is a widely adopted life cycle impact assessment framework that converts emissions and resource use into 18 midpoint impact categories, such as global warming, water consumption and fossil resource scarcity. The midpoint indicators quantify specific environmental burdens along the cause-effect chain (e.g., kg CO₂-equivalent for global warming), whereas endpoint indicators further aggregate these results into broader areas of damage, such as human health, ecosystem quality and resource availability, which is beyond the scope of the present work.

In addition to the assessment method, a cut-off allocation approach was employed herein, which assigns all upstream environmental burdens to the primary product, while excluding co-products and recycled materials from the system boundary [36, 37]. Under this convention, recycled inputs enter the system burden-free, and no environmental credit is given for recyclable outputs leaving the system.

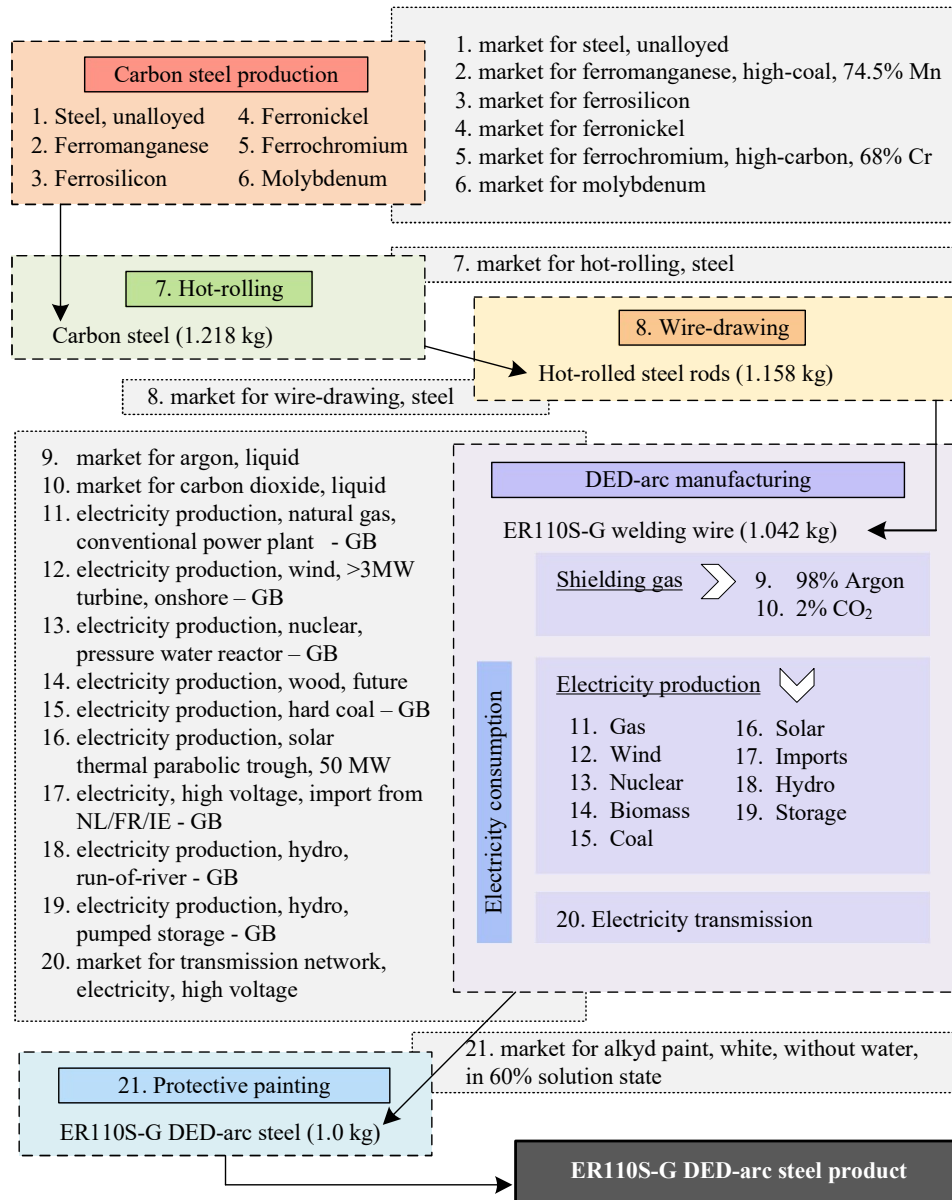


Figure 7: Life cycle assessment model graph for the production of a unit mass (1 kg) of ER110S-G DED-arc steel.

3.6. Results and discussion

The results of the ReCiPe midpoint (H) life cycle impact assessment for the unit-mass productions are summarised in Table 5, where the environmental impacts are reported across 18 midpoint impact categories. Fig. 8 presents the normalised impact results, where the impact values are normalised by the maximum value among the four types of steel within each category. In general, S355 hot-rolled steel exhibits lower environmental impact per unit-mass in nearly all categories compared to the DED-arc steels. In particular, the DED-arc steels are approximately twice as impactful per unit-mass as the S355 hot-rolled steel in terms of global warming, as quantified in Table 5 using the metric – global warming potential (GWP, unit: kg CO₂ eq). For those impact categories related to ecotoxicity, namely freshwater, marine and terrestrial ecotoxicity, the two high-strength DED-arc steels show substantially higher impacts than the normal-strength ER70S-2 DED-arc steel and the S355 hot-rolled steel. More specifically, the ER110S-G and the ER110S-G DED-arc steel are 2.7 and 2.9 times more impactful, respectively, than the S355 hot-rolled steel, in terms of terrestrial ecotoxicity. This is primarily owing to the additional alloying elements used in high-strength steel production, as discussed later.

To examine the underlying environmental mechanisms further, the contributions of each individual production stage to the overall environmental impacts are shown in Fig. 9 for the four steel types, across some selected impact categories covering climate change, water depletion and pollution, and human health. The corresponding data per unit-mass production are summarised in Tables A6–A9 in Appendix A. At the steel production stage, the GWP of the ER70S-2 steel, 2.150 kg CO₂ eq, is only slightly higher than that of the S355 steel, 1.957 kg CO₂ eq; however, this value rises to 2.756 kg CO₂ eq and to 2.875 kg CO₂ eq for the two high-strength steels – ER110S-G and ER120S-G, respectively. These higher emissions are primarily attributed to the greater alloying contents in the high-strength steels, particularly owing to the presence of nickel. For instance, the ferronickel addition contributes nearly 30% of the total GWP of the ER110S-G steel production, despite nickel accounting for only 1.85% of the total weight. This is owing to the inherently carbon-intensive nature of nickel production [48, 49]. The wire drawing and the DED-arc manufacturing together contributes substantially (i.e., approximately 35%) to the total GWP of the DED-arc steel production, where about half of this share arises from the consumption of shielding gases (98% Ar + 2% CO₂). The shielding gases are also found to have a notable influence on the water consumption, contributing approximately 50% of the total water consumption in DED-arc steel production. In addition, the alloying contents are found to be major contributors to the human carcinogenic toxicity and freshwater ecotoxicity, with manganese and molybdenum identified as the primary impact sources for these two categories, respectively. This is owing to the ferromanganese production typically releasing polycyclic aromatic hydrocarbons, which are carcinogenic [50], while the molybdenum production emits heavy metals such as lead and mercury into water bodies, increasing aquatic toxicity [51].

3.7. Sensitivity study

The environmental impacts of the hot-rolled and DED-arc steels have been evaluated in the preceding sections through cradle-to-gate LCA, using the material chemical composition provided by the material suppliers and the process parameters adopted in the physical experiments. However, the resulting impact values are hence limited to these specific input data and modelling assumptions. Therefore, to assess the generalisability of the impact results, a series of sensitivity studies are conducted in this section to examine the influence of variations in chemical composition, electricity mix and modelling assumptions on the environmental impacts of the examined steels.

The production of DED-arc steels was modelled using the default reference process '*market for steel, unalloyed*' as the base inventory, which contains no additional alloying elements other than carbon. The remaining alloying elements were then manually added according to the chemical compositions provided in the respective welding wire specifications. It should be noted that welding wires from different production batches or suppliers may exhibit variations in chemical composition. A sensitivity analysis was therefore conducted to evaluate the influence of variations in alloying-element content on the environmental impacts of DED-arc steels, with particular focus on Ni, Mn and Mo, as these elements have a pronounced influence on GWP and toxicity-related impact categories. To define representative variation ranges, a series of ER110S-G welding wire certificates and specification sheets was collected from multiple suppliers [52–57]. Based on these sources, the typical composition ranges of Ni, Mn and Mo were identified as 1.60%–2.40%, 1.40%–1.85% and 0.20%–0.60%, respectively. The ER110S-G composition reported in Table 2 was adopted as the benchmark case, while the content of Ni, Mn or Mo was varied individually within its corresponding typical range. Only one alloying element was varied at a time, with all other alloying elements kept unchanged. The Fe content was correspondingly varied to ensure mass conservation. The results of the sensitivity study are shown in Table 6. It can be observed that GWP is insensitive to variations in the alloying-element contents. However, human carcinogenic toxicity is relatively sensitive to variations in Mn content, with a 0.45% increase in Mn leading to a 16% increase in its value. Similarly, freshwater ecotoxicity is relatively sensitive to variations in Mo content, with a 0.40% increase in Mo leading to an 88% increase in its value.

The electricity mix in Section 3.3 was modelled using data from the UK National Energy System Operator (NESO), with renewable energy accounting for approximately 45% of the total supply. However, this regional electricity mix may not fully capture the influence of different energy systems on the environmental impacts of the examined steels. Therefore, a sensitivity study was conducted by varying the proportion of renewable energy in the electricity mix. Two artificial scenarios were defined: (a) 0% renewable energy, consisting of 97% natural gas and 3% coal; and (b) 100% renewable energy, consisting of 68% wind, 15% biomass, 5% hydro and 12% solar. It should be noted that the electricity mix was applied only to the electricity consumed during the DED-arc process. The sensitivity of GWP to the electricity mix is summarised in Table 7. The results show that using a 100% renewable electricity mix instead

of a 0% renewable mix can reduce the GWP by approximately 15%. The potential influence of electricity mix on the environmental implications of hybrid DED-arc-hot-rolled beams is briefly discussed in the following section.

In Section 3.3, the emissions from arc welding were adopted from the default *welding, arc, steel* reference process in Ecoinvent [37]. In practical welding applications, however, these emissions may vary depending on process parameters, material chemical composition and welding efficiency. A sensitivity study was therefore conducted by artificially varying the emission quantities from 50% to 300% of the default values, after which the corresponding midpoint impacts were evaluated. The results show that the midpoint impacts are generally insensitive to variations in the welding emissions; more specifically, for the ER110S-G DED-arc steel, 17 of the 18 midpoint impact categories exhibited differences of less than 2%, with terrestrial ecotoxicity being the only exception, showing a moderate difference of 8%.

It should be noted that, for consistency with the physical experiments, the unit-mass impact results presented in Section 3.6 are used in the following section to evaluate the environmental implications of the hybrid DED-arc-hot-rolled beams. The sensitivity study results presented herein are therefore supplementary.

Table 5: ReCiPe midpoint impact results for production of 1 kg S355 hot-rolled steel I-section, ER70S-2, ER110S-G and ER120S-G DED-arc steel.

Category	Unit	S355 steel	ER70S-2 DED-arc steel	ER110S-G DED-arc steel	ER120S-G DED-arc steel
Fine particulate matter formation	kg PM _{2.5} eq	5.06E-03	7.33E-03	1.02E-02	1.05E-02
Fossil resource scarcity	kg oil eq	0.596	1.019	1.262	1.289
Freshwater ecotoxicity	kg 1,4-DCB	0.199	0.249	1.087	1.095
Freshwater eutrophication	kg P eq	0.001	0.002	0.003	0.003
Global warming	kg CO ₂ eq	2.493	4.191	5.126	5.237
Human carcinogenic toxicity	kg 1,4-DCB	3.017	2.920	3.527	3.621
Human non-carcinogenic toxicity	kg 1,4-DCB	2.674	3.657	12.767	12.969
Ionizing radiation	kBq Co-60 eq	0.090	0.684	0.911	0.914
Land use	m ² a crop eq	0.106	0.175	0.189	0.193
Marine ecotoxicity	kg 1,4-DCB	0.277	0.345	1.398	1.410
Marine eutrophication	kg N eq	1.92E-04	2.13E-04	2.66E-04	2.70E-04
Mineral resource scarcity	kg Cu eq	0.129	0.107	0.280	0.302
Ozone formation, Human health	kg NO _x eq	0.006	0.009	0.012	0.013
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.007	0.010	0.013	0.013
Stratospheric ozone depletion	kg CFC11 eq	7.63E-07	1.36E-06	1.88E-06	1.92E-06
Terrestrial acidification	kg SO ₂ eq	0.009	0.013	0.018	0.019
Terrestrial ecotoxicity	kg 1,4-DCB	13.630	9.265	36.441	39.320
Water consumption	m ³	0.030	0.088	0.111	0.111

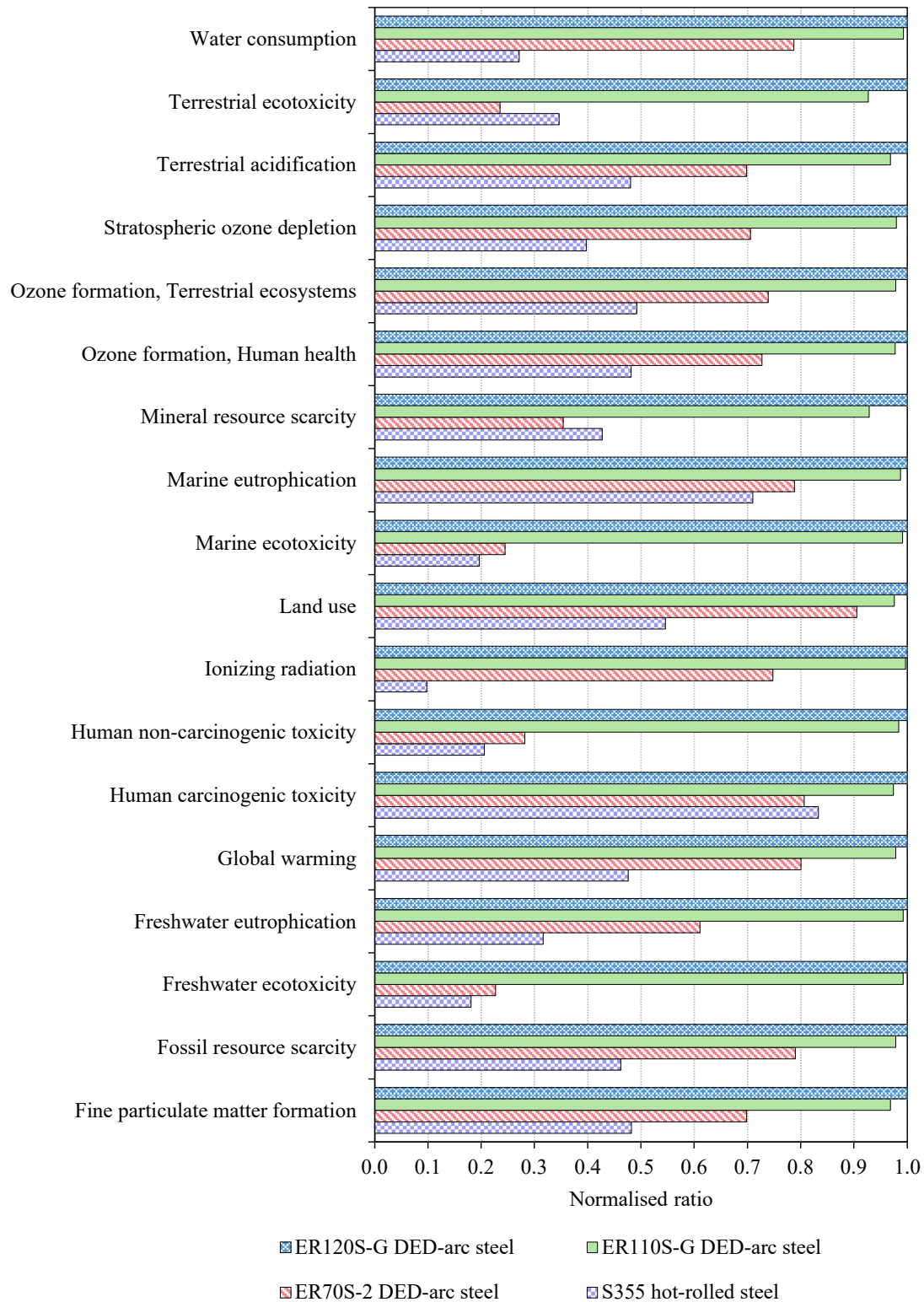
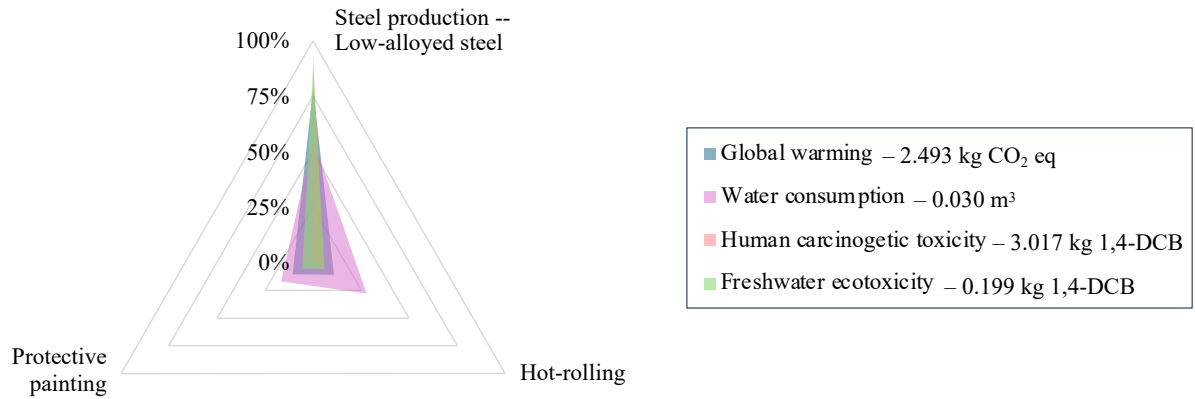
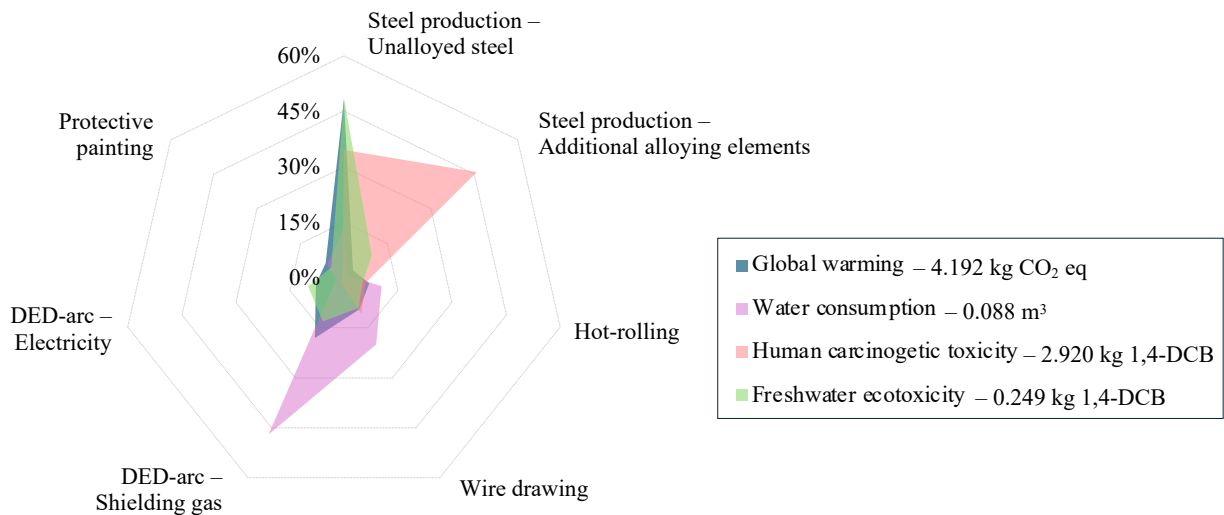


Figure 8: Normalised impact results for the unit-mass production of S355 hot-rolled steel, ER70S-2, ER110S-G and ER120S-G DED-arc steel.

LCA – hybrid DED-arc-hot-rolled steel beams



(a)



(b)

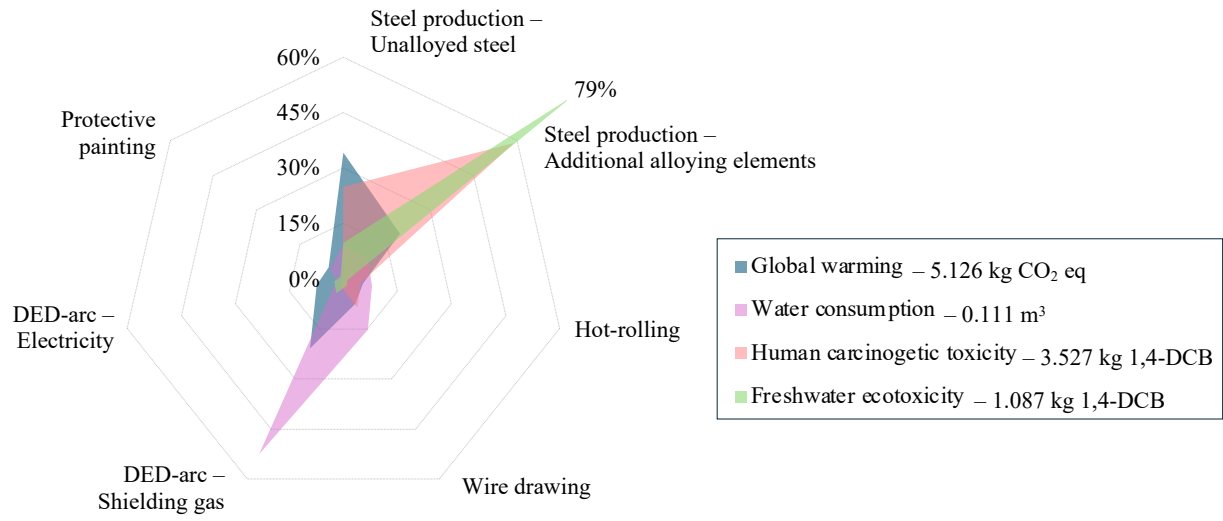
Figure 9: Contributions of individual production stage to the overall environmental impacts for (a) S355 hot-rolled steel, (b) ER70S-2 DED-arc steel, (c) ER110S-G DED-arc steel and (d) ER120S-G DED-arc steel.

Table 6

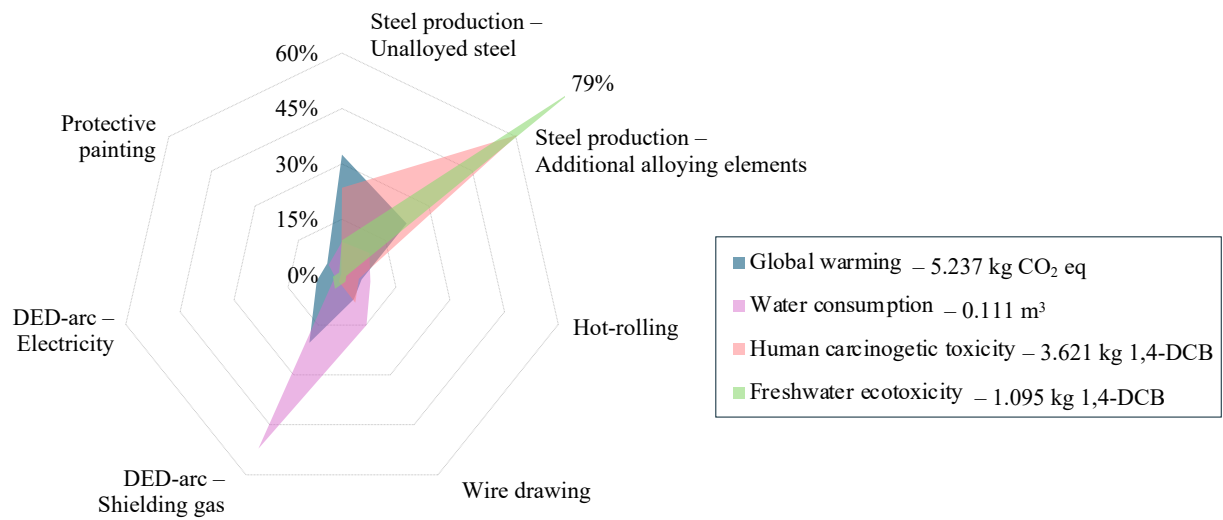
Typical environmental impacts associated with producing one kg of ER110S-G DED-arc steels considering variations in alloying elements.

Alloying element	Ni	Mn	Mo
Typical range	1.60%–2.40%	1.40%–1.85%	0.20%–0.60%
Global warming potential (GWP) (kg CO ₂ eq)	5.035–5.326	5.118–5.130	5.058–5.126
Human carcinogenic toxicity (kg 1,4-DCB)	3.523–3.535	3.183–3.699	3.499–3.527
Freshwater ecotoxicity (kg 1,4-DCB)	1.079–1.106	1.082–1.089	0.578–1.087

LCA – hybrid DED-arc-hot-rolled steel beams



(c)



(d)

Figure 9: (Continued) Contributions of individual production stage to the overall environmental impacts for (a) S355 hot-rolled steel, (b) ER70S-2 DED-arc steel, (c) ER110S-G DED-arc steel and (d) ER120S-G DED-arc steel.

Table 7

GWP per kg of examined DED-arc steels using different electricity mix (unit: kg CO₂ eq).

Electricity mix	ER70S-2	ER110S-G	ER120S-G
0% renewable	4.689	5.677	5.795
UK mix (45% renewable)	4.191	5.126	5.237
100% renewable	3.910	4.801	4.919

4. Analysis on hybrid I-section beams

In Section 3, material-level life cycle impact assessments were carried out, while in the current section, the carbon footprints of the hybrid beam specimens described in Section 2 are evaluated at the member level, using the unit-mass impact results from Section 3. Since beams are the dominant structural elements in steel buildings, the findings presented in this section are representative of the structural-level implications of hybrid steel construction featuring DED-arc.

4.1. Functional unit

For each hybrid beam specimen in Table 1 with a span L and a design bending moment resistance $M_{Rd,H}$, a functional unit is defined as a beam of length L capable of withstanding a design bending moment M_{Ed} , where $M_{Ed} = M_{Rd,H}$. Accordingly, for each hybrid specimen, a functionally equivalent bare I-section beam, denoted as bare I-section-eq, was selected from either the British Universal Beam (UB) section tables [58] or the European IPE section tables. The selected bare I-section-eq has a design bending moment resistance $M_{Rd,I,eq}$ that is the closest greater value to its corresponding M_{Ed} , thereby enabling a functionally equivalent comparison with its hybrid counterpart.

According to the design provisions of EN 1993-1-1 [34], all I-section profiles in the UB and the IPE section tables are classified as Class 1 under bending; therefore, the value of $M_{Rd,I,eq}$ was taken as the major-axis plastic bending moment resistance, $M_{pl,y}$, of the I-section [34]. For a hybrid beam specimen with non-uniform cross-sections along its length, the value of $M_{Rd,H}$ was taken as the value of $M_{pl,y}$ of the mid-span cross-section [18], calculated based on the full-plastic stress distribution illustrated in Fig. 4. The experimental results summarised in Section 2 have shown that the ultimate bending moment resistances, M_u of all hybrid beam specimens exceeded their corresponding calculated values of $M_{Rd,H}$, owing particularly to strain hardening [59, 60].

The functional equivalence adopted herein is defined with respect to design bending resistance, which is appropriate for the current LCA framework adopting a cradle-to-gate system boundary and considering only the production activities. However, long-term structural performance such as durability, fatigue performance, inspection requirements and maintenance needs are not explicitly included in the present system boundary. Future studies should combine these long-term aspects with broader cradle-to-grave system boundaries, such that the use-phase performance, maintenance, repair, service-life extension and end-of-life scenarios can be incorporated into the LCA framework to evaluate the whole-life environmental implications of hybrid steel beams.

4.2. Results and discussion

Table 8 summarises the information on the examined hybrid beam specimens and of their corresponding bare I-sections-eq, where m , m_I and m_W are the total mass, the mass of the I-section and the mass of the DED-arc(welded) addition, respectively. Likewise, GWP, GWP_I and GWP_W denote the total global warming potential, the contribution from the hot-rolled I-section, and the contribution from the DED-arc addition, respectively. Further, ϕ is defined as the ratio between the GWP of the hybrid beam specimen and that of its corresponding bare I-section-eq. The GWP values are calculated based on the impact results of the unit-mass productions – see Table 5 – and the mass information of the examined beams.

Table 8: Global warming potential of the examined hybrid beam specimens and corresponding functionally equivalent bare I-section beams (* indicates 'bare I-section-eq', 4PB – four-point bending, 3PB – three-point bending).

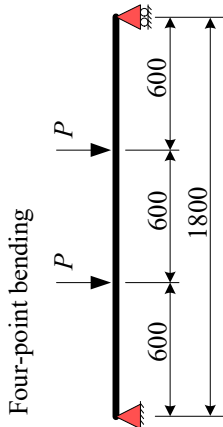
Loading condition	Beam	M_{Rd} (kNm)	m_I	m_w (kg)	m	GWP_I	GWP_w (kg CO2 eq.)	GWP	φ
Four-point bending 	ER70-4PB-10% IPE180*	61.99 68.22	28.89 33.88	3.37 –	32.26 33.88	72.02 84.46	14.12 –	86.15 84.46	1.02
	ER110-4PB-5% IPE180*	62.17 68.22	28.73 33.88	1.67 –	30.40 33.88	71.62 84.46	8.56 –	80.18 84.46	0.95
	ER110-4PB-10% IPE200*	72.18 90.45	29.10 40.30	3.19 –	32.29 40.30	72.55 100.47	16.35 –	88.90 100.47	0.88
	ER110-4PB-15% IPE200*	79.22 90.45	28.70 40.30	4.42 –	33.12 40.30	71.55 100.47	22.66 –	94.21 100.47	0.94
	ER120-4PB-5% IPE180*	63.56 68.22	28.66 33.88	1.73 –	30.39 33.88	71.45 84.46	9.06 –	80.51 84.46	0.95
	ER120-4PB-10% IPE200*	72.39 90.45	28.50 40.30	3.34 –	31.84 40.30	71.05 100.47	17.49 –	88.54 100.47	0.88
	ER120-4PB-15% IPE200*	81.36 90.45	28.73 40.30	4.34 –	33.07 40.30	71.62 100.47	22.73 –	94.35 100.47	0.94

Table 8: (continued) Global warming potential of the examined hybrid I-section beam specimens and corresponding functionally equivalent bare I-section beams (* indicates 'bare I-section-eq', 4PB – four-point bending, 3PB – three-point bending).

Loading condition	Beam	M_{Rd} (kNm)	m_l	m_w (kg)	m	GWP _l	GWP _w	GWP	φ
Three-point bending	ER70-3PB-10% UB178x102x19*	68.96 70.22	28.81 34.20	3.18 –	31.99 34.20	71.82 85.26	13.33 –	85.15 85.26	1.00
	ER110-3PB-5% IPE200*	76.13 90.45	29.13 40.30	1.64 –	30.77 40.30	72.62 100.47	8.41 –	81.03 100.47	0.81
	ER110-3PB-10% IPE200*	86.52 90.45	28.92 40.30	3.10 –	32.02 40.30	72.10 100.47	15.89 –	87.99 100.47	0.88
	ER110-3PB-15% UB203x133x25*	98.49 105.67	28.82 45.18	4.46 –	33.28 45.18	71.85 112.63	22.86 –	94.71 112.63	0.84
	ER120-3PB-5% IPE200*	75.35 90.45	29.22 40.30	1.61 –	30.83 40.30	72.85 100.47	8.43 –	81.28 100.47	0.81
	ER120-3PB-10% IPE200*	84.33 90.45	28.73 40.30	2.97 –	31.70 40.30	71.62 100.47	15.55 –	87.18 100.47	0.87
	ER120-3PB-15% UB203x133x25*	96.80 105.67	28.92 45.18	4.45 –	33.37 45.18	72.10 112.63	23.30 –	95.40 112.63	0.85

For a hybrid beam, its capability of reducing GWP relative to its bare I-section-eq primarily relies on the extent of the overall mass reduction, since the production of DED-arc steel is significantly more carbon intensive than the production of hot-rolled steel – see Table 5. It can be observed from Table 8 that all hybrid specimens yield reductions in mass compared with their respective bare I-sections-eq. The ER110-S355 and the ER120-S355 hybrid beam specimens show reductions in GWP of between 5% to 19%, indicating improved sustainability. However, the two ER70-S355 hybrid beam specimens exhibit GWP values approximately equal to or slightly higher than those of their bare I-section counterparts. This outcome arises since the mass reductions in the ER110-S355 and ER120-S355 hybrid specimens, achieved through the addition of optimised high-strength DED-arc steels, outweighed the heavier burden of the CO₂ emissions associated with the DED-arc steel production; the opposite trend is, however, found for those normal-strength ER70-S355 hybrid specimens.

To quantify the extent of mass reduction required for a hybrid beam to achieve a lower GWP, and thereby be more sustainable, compared to its bare I-section-eq, a sustainability bound can be established, on which the GWP of the hybrid beam, g_H , and that of the corresponding bare I-section-eq, $g_{I,eq}$, are equal. The quantities – g_H and $g_{I,eq}$ – can be expressed as:

$$g_H = \bar{g}_I m_{I,H} + \bar{g}_W m_{W,H} \quad (1)$$

and

$$g_{I,eq} = \bar{g}_I m_{I,eq}, \quad (2)$$

where $\bar{g}_I$ is the GWP per unit-mass of hot-rolled S355 steel, $\bar{g}_W$ is the GWP per unit-mass of DED-arc steel – see Table 5; $m_{I,H}$ and $m_{W,H}$ are the masses of the I-section portion and the DED-arc portion of the hybrid beam, respectively, while $m_{I,eq}$ is the mass of the bare I-section-eq. Substituting $m_{I,H} = m_H - m_{W,H}$, where m_H is the total mass of the hybrid beam, into the previous equations yields:

$$\frac{m_H}{m_{I,eq}} = \frac{1}{\left(\frac{\bar{g}_W}{\bar{g}_I} - 1\right) \frac{m_{W,H}}{m_H} + 1}, \quad (3)$$

where the term $m_H/m_{I,eq}$ is referred to as the mass ratio; and the term $m_{W,H}/m_H$ as the hybrid rate.

In Fig. 10, three sustainability bounds are plotted for the ER70-S355, ER110-S355 and ER120-S355 hybrid beams, respectively, together with the data of the tested hybrid specimens [18, 19]. It can be observed that the ER110/120-S355 hybrid specimens, with relatively high overall mass reductions, lie below the bounds, indicating improved sustainability; whereas the ER70-S355 hybrid specimens are located on or slightly above the sustainability bounds, implying comparable sustainability relative to the conventional bare I-section counterparts.

Compared with the LCA results reported by Shah et al. [33], where an approximately 50% mass reduction was required for a fully additively manufactured DED-arc structural component to achieve a lower GWP than its conventional hot-rolled counterpart, the sustainability bounds shown in Fig. 10 indicate that the hybrid manufacturing strategy can reduce embodied carbon with substantially smaller mass reductions. For example, for ER120-S355 hybrid beams, a moderate overall mass reduction of only 10% is sufficient for the hybrid beam to achieve a lower GWP than the corresponding conventional hot-rolled beam at a hybrid rate of 0.1.

As discussed in the sensitivity study presented in Section 3.7, increasing the proportion of renewable energy in the electricity mix reduces the GWP of the DED-arc steels. Fig. 11 presents the sustainability bounds for hybrid beams manufactured using electricity mixes with different renewable energy shares. The results show that a higher proportion of renewable energy lowers the mass-reduction threshold required for hybrid beams to achieve lower embodied carbon/GWP than their conventional hot-rolled counterparts.

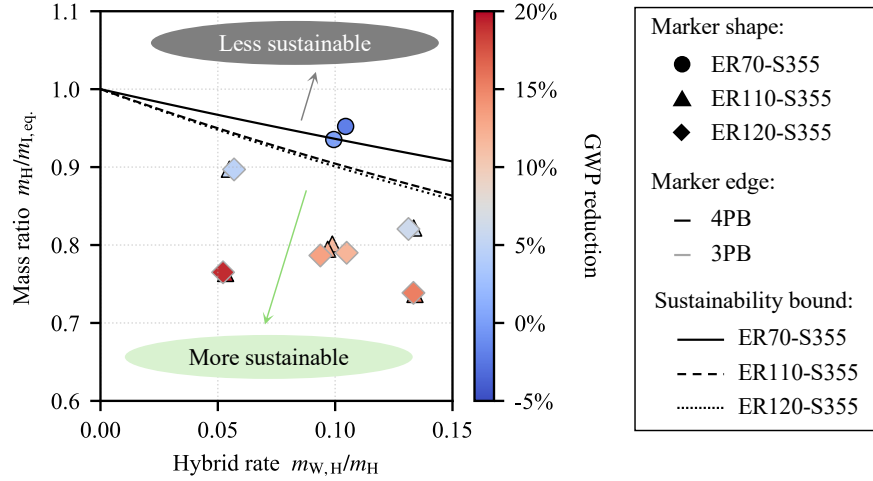


Figure 10: Sustainability bounds and GWP reductions of hybrid beam specimens.

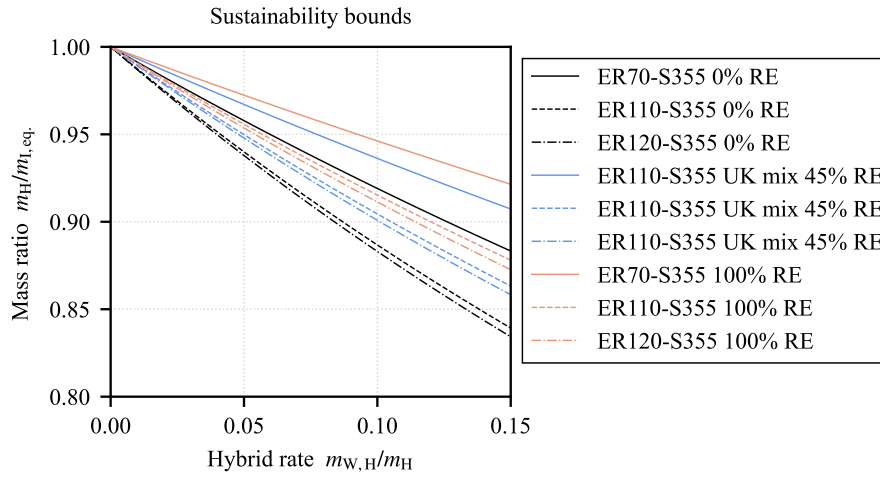


Figure 11: Sustainability bounds of hybrid DED-arc-hot-rolled beams manufactured using different levels of renewable energy in electricity mix (RE-renewable energy).

5. Parametric study

In Section 4, the member-level environmental impacts of a series of tested hybrid beam specimens were assessed, with most of the hybrid specimens exhibiting lower GWP values relative to their conventional bare I-section counterparts. However, those hybrid specimens only represent a limited set of beam configurations, hybrid rates and loading scenarios; meanwhile the overall influence of the hybrid DED-arc-hot-rolled manufacturing strategy on the global warming potential of steel beam design still remains unclear. Therefore, a comprehensive parametric study is carried out in this section, covering a wide range of beam geometries, hybrid rates and loading conditions, to establish a broader understanding of the sustainability potential of hybrid DED-arc-hot-rolled steel I-section beams.

5.1. General

A parametric framework was established comprising a total of 40000 design cases, with each case verified against both ultimate limit state (ULS) and serviceability limit (SLS) criteria. At ULS, beams were designed in compliance with EN 1993-1-1 [34] to sustain the design bending moment, M_{Ed} , and the design shear force, V_{Ed} ; while at SLS, the beam

Table 9

Examined parameters for parametric study.

Parameter	Description	Range
Loading condition	–	4PB, 3PB, UDL, 4PB+UDL, 3PB+UDL – see Fig. 12
M_{Ed}	Design bending moment sampled from Fig. 13	(34, 9415) unit: kNm
$L/H_{I,eq}$	Span-to-depth ratio of bare I-section-eq	[9, 20]
α	Live-to-dead load ratio	[1, 3]
DED-arc steel	–	ER70S-2 (as built $f_y = 375$ MPa) ER110S-G (as built $f_y = 590$ MPa)
β	UDL proportion	(0, 1)

deflections were verified against the live (variable) load deflection limit of 1/200 of the beam span. Each design case was defined by six parameters. The descriptions and ranges of these defining parameters are summarised in Table 9.

A total of five typical loading conditions within steel beam design were considered in the present study, as listed in Table 9 and illustrated in Fig. 12, showing the corresponding bending moment diagrams. The design bending moment, M_{Ed} , is defined as the largest bending moment acting along the beam span. The value of M_{Ed} was randomly sampled from the distribution of $M_{pl,y}$ of all UB sections (see Fig. 13), ranging from 34 to 9514 kNm and determined assuming a yield strength f_y of 410 MPa, consistent with Section 4. The quantities L and $H_{I,eq}$ in Table 9 are the span and the height of the bare I-section-eq, respectively.

The design bending moment range, $M_{Ed}=34\text{--}9415$ kNm, reflects the resistance of all UB I-section profiles, which covers a wide range of applications including relatively small secondary beams, typical floor beams, larger primary beams and heavily loaded transfer beams. The lower end of the range is therefore representative of lightly loaded members, while the upper end corresponds to sections used for heavy loading demands. Adopting such a broad range enables an assessment of the applicability of the hybrid manufacturing strategy across a wide design space.

In steel structures, the members are typically subjected to dead and live loads (also referred to as permanent and variable actions). Here, a live-to-dead load ratio, α , is defined to decompose the overall M_{Ed} into contributions from the live load and from the dead load, respectively. The value of M_{Ed} can be expressed thus:

$$M_{Ed} = 1.35M_G + 1.5M_Q, \quad (4)$$

where M_G and M_Q are the unfactored bending moment contributions from the dead load and the live load, respectively – see Fig. 13, and $\alpha = M_Q/M_G$. The partial factors 1.35 and 1.5 were adopted from EN 1990 [61] for ULS design. For the ‘4PB+UDL’ and ‘3PB+UDL’ loading conditions, an additional parameter, β , is introduced to characterise the proportion of the overall M_{Ed} resulting from the UDL. A value of 0 for β corresponds to pure three-point or four-point bending, whereas a value of 1 corresponds to a pure UDL condition. Note that all the defining parameters described above, except M_{Ed} , were randomly sampled from uniform probability distributions for each design case.

5.2. Beam design

For each design case, a bare I-section-eq was first selected, followed by a series of hybrid beams. The overall design flow is illustrated in Fig. 15. Note that the bare I-section-eq was selected in each design case as the lightest I-section among all the valid I-sections from the UB section tables satisfying $M_{Rd} > M_{Ed}$, and is therefore deemed to be the most sustainable option. In the UB section tables, some I-section profiles may exhibit similar bending moment resistance, M_{Rd} , but considerably different strength-to-weight ratios, η , defined as the ratio between M_{Rd} and the mass of the section profile per metre. The values of η for all UB I-sections are plotted against the corresponding M_{Rd} and cross-section height, H , in Fig. 14(a) and (b) respectively. The points highlighted in red represent the I-section profiles with the highest η value at various levels of M_{Rd} . Essentially, the I-section-eq was selected from those highlighted profiles in each design case.

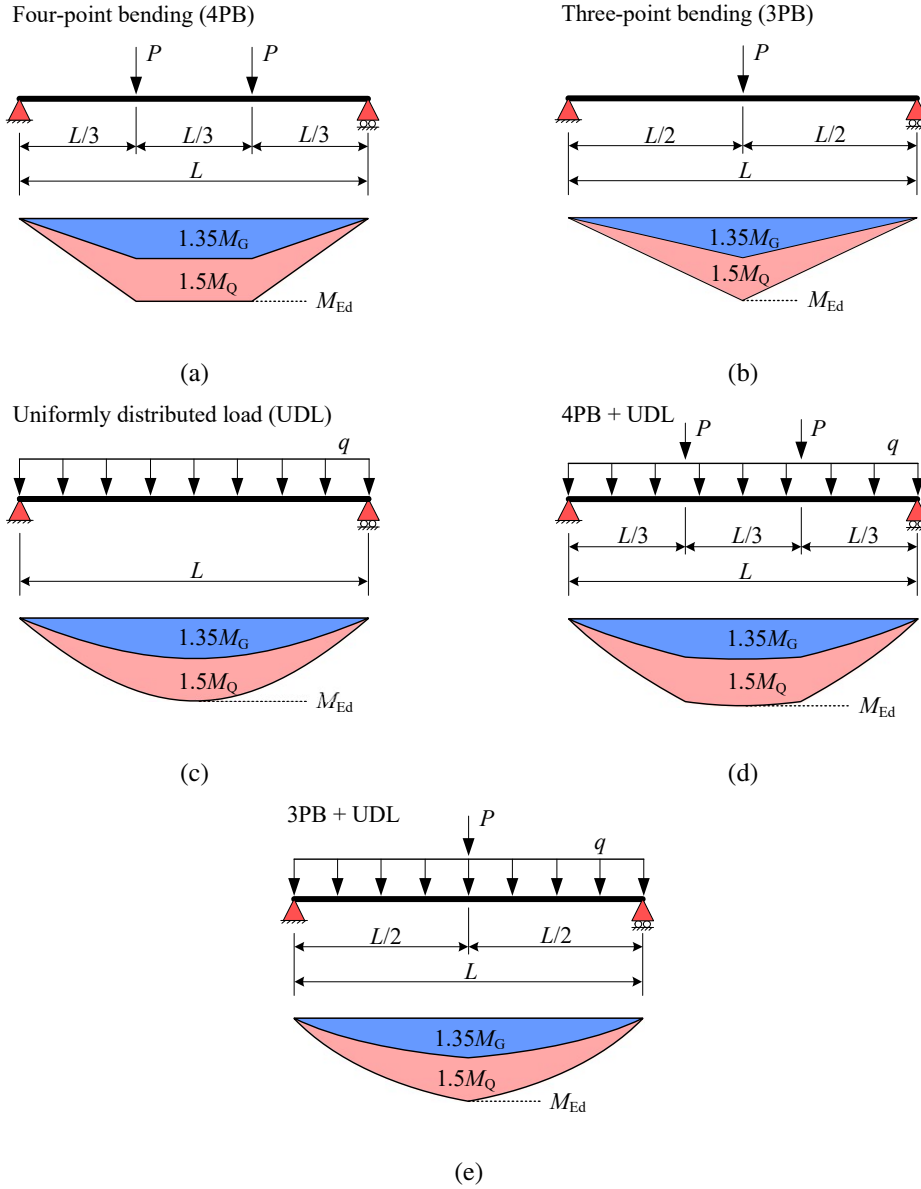


Figure 12: Loading conditions employed in parametric study.

The design of each hybrid beam initiated with the selection of a base I-section that is shallower in height and has a lower M_{Rd} than the previously designed bare I-section-eq. The DED-arc steel additions were then designed and optimised following the method and rules described in [18] and Section 2, to achieve the required resistance capable of sustaining the applied M_{Ed} . Note that the mid-height plastic neutral axis of all hybrid cross-sections along the beam length was maintained. Note also that all I-sections-eq designed in this parametric study were governed by their bending moment resistances, whereas deflection-governed and shear-governed cases were excluded, as reflected in Fig. 15. This limitation arises since the design and optimisation method developed for the hybrid beams was inherently established for the M_{Rd} -governed scenario and is not readily applicable for other scenarios; consideration of the cases not covered herein are left for future work.

The weld bead geometries given in Table 3 were adopted for the hybrid beam design. The configuration of a typical hybrid cross-section is illustrated in Fig. 15. For the DED-arc stiffeners deposited on the flange tips, the number of weld passes within each layer was determined as $n = t_f/b_W$, with n rounded to the nearest integer. On the tension flange, each layer accommodates as many weld passes as possible, with the final layer being partially filled depending on the optimised design results.

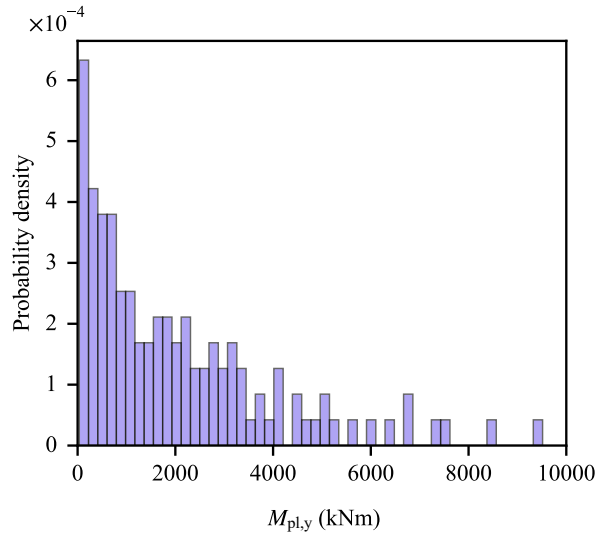


Figure 13: Probability density of $M_{pl,y}$ of UB I-sections (i.e., $M_{pl,y} = M_{Rd}$ in the present study).

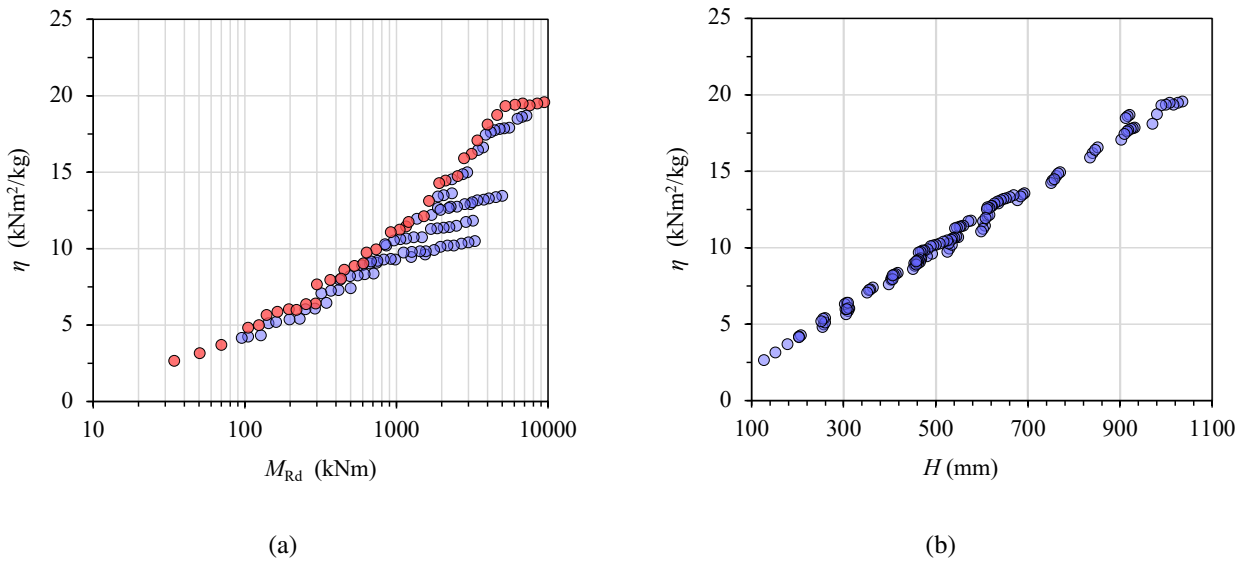


Figure 14: Strength-to-weight ratio, η , of UB I-sections against (a) bending moment resistance, M_{Rd} , (horizontal axis in logarithmic scale, base 10) and (b) cross-sectional height, H .

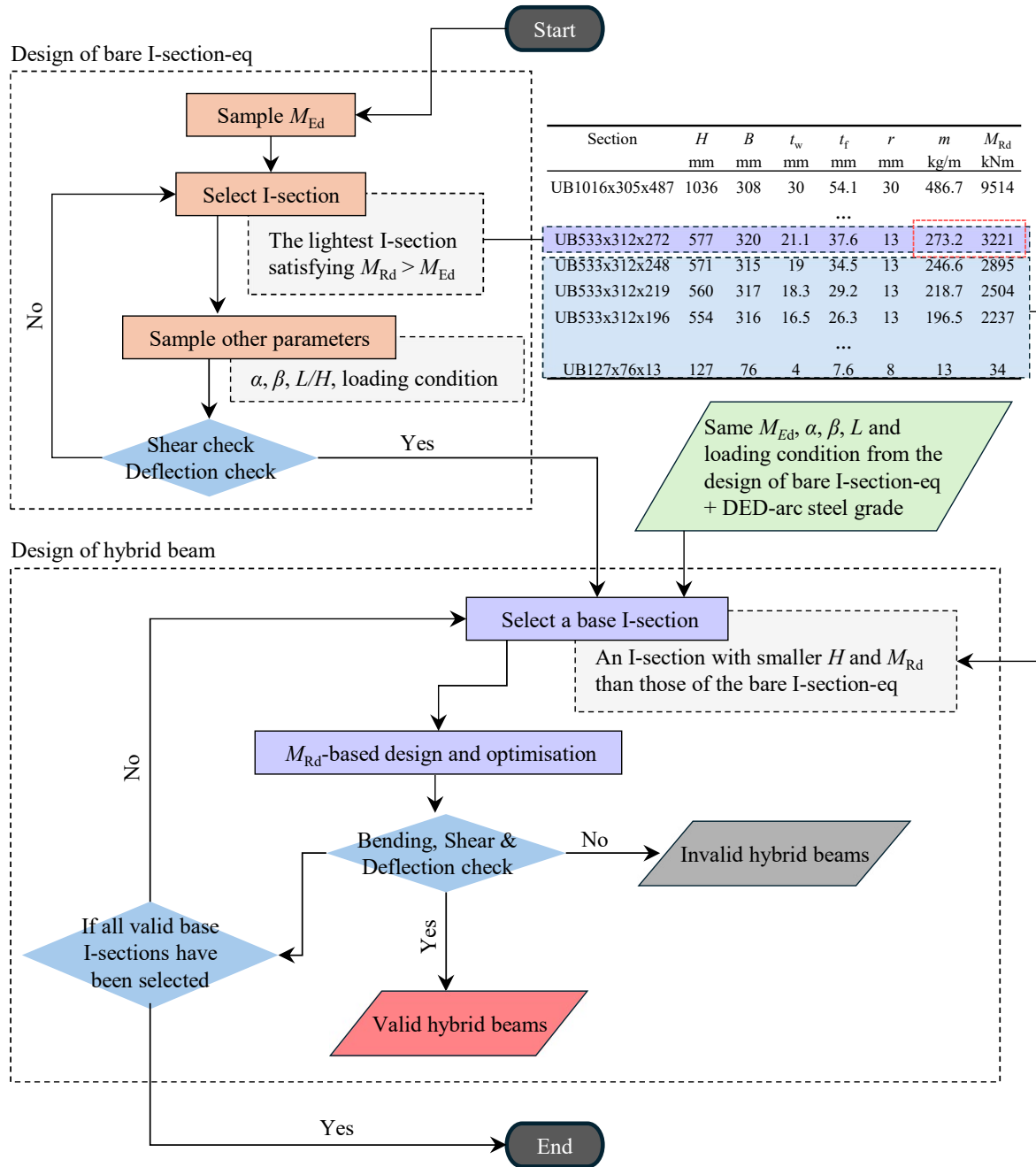


Figure 15: Design flow chart for bare I-section-eq and hybrid beams.

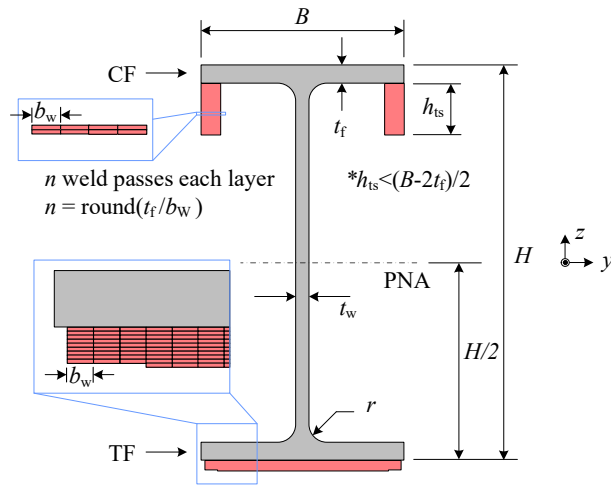


Figure 16: Geometry and configuration of a typical hybrid cross-section (TF – tension flange, CF – compression flange, PNA – plastic neutral axis).

5.3. Impact assessment

The results of a typical design case are presented in Fig. 17, where the GWP values of the designed hybrid beams, normalised by that of the bare I-section-eq – denoted as GWP^* – are plotted against the hybrid rates, $m_{W,H}/m_H$. In Fig. 17, each data point represents a designed hybrid beam; all hybrid beams satisfied the ULS design requirements, while those that failed the SLS verification due to excessive deflection are highlighted in purple. In the upper left corner of Fig. 17, hybrid beams with GWP^* values significantly higher than unity can be observed at relatively low hybrid rates. In these cases, the base I-sections within the hybrid beams typically have bending moment resistances slightly lower than that of the bare I-section-eq, and therefore require only a small amount of DED-arc additions to achieve the target bending moment resistance for the hybrid beam. Consequently, the base I-section dominates the overall GWP of these hybrid beams. However, these base I-sections generally exhibit much lower strength-to-weight ratios, owing to their reduced depth-to-width ratios, H/B , compared to the bare I-section-eq, see Fig. 14(b). Hence, these base I-sections are often heavier on their own than the bare I-section-eq, resulting in GWP^* values higher than 1, as illustrated in Fig. 17. Conversely, on the right side of Fig. 17, the hybrid beams typically comprise base I-sections that are considerably smaller (i.e., with much lower bending moment resistance) than the bare I-section-eq, and therefore require relatively high hybrid rates to achieve the target bending moment resistance. However, the reduced flexural stiffness of these hybrid beams – primarily owing to the smaller cross-sectional height – generally leads to excessive deflections that fail to meet the serviceability criteria. Among all verified hybrid beams, the one with the lowest GWP^* value, referred to as the optimal sustainable beam, was identified at a hybrid rate of approximately 9%, while achieving a reduction in GWP of approximately 22% relative to the bare I-section-eq.

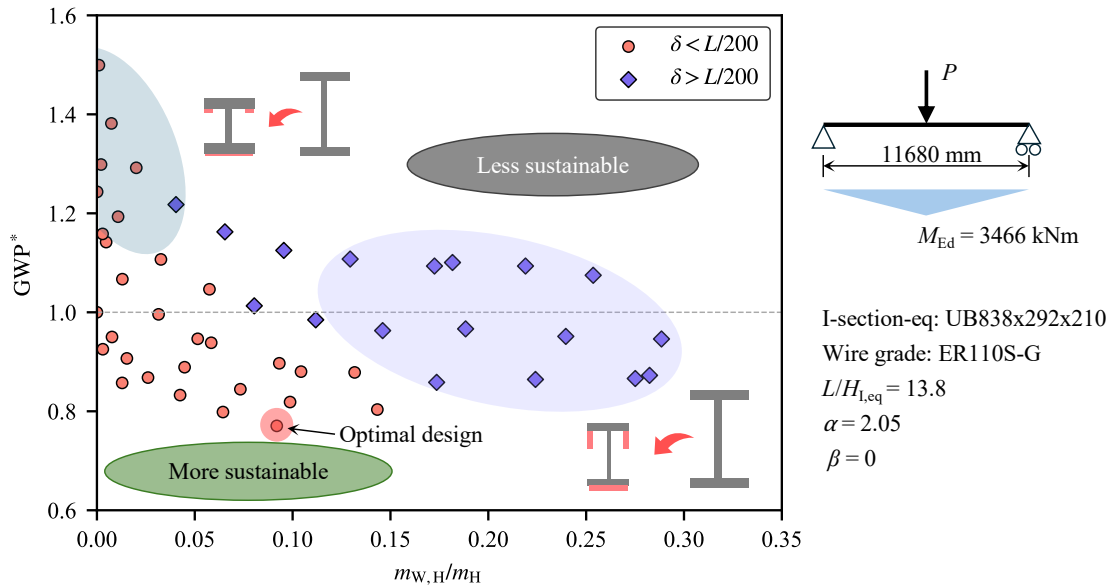


Figure 17: Hybrid beam design results for a typical design case (δ – beam deflection, shaded areas only for illustration purpose).

To examine the hybrid design framework further, the span-to-deflection ratios of those hybrid beams shown in Fig. 17 are plotted against the hybrid rates in Fig. 18. In this specific design case, the bare I-section-eq exhibits a span-to-deflection ratio of approximately 1/400, which is notably smaller than the serviceability limit, 1/200, indicating a relatively high redundancy in flexural stiffness. Overall, it can be observed from Fig. 18 that the relative deflection of the hybrid beams increases with increasing hybrid rate, with that of the optimal sustainable beam approaching the serviceability limit, $L/200$. Hence, it can be concluded that, in the optimal sustainable beam, the material redundancy was effectively reduced through the structural optimisation – see Fig. 3, while, consequently, flexural stiffness becomes more critical. This phenomenon is further demonstrated by the probability distributions of $L/\delta_{I,eq}$ and of L/δ_{opt} across all the examined design cases, as shown in Fig. 19, where δ_{opt} is the deflection of the optimal sustainable beam and $\delta_{I,eq}$ is the deflection of the bare I-section-eq in each design case. It can be observed from Fig. 19 that, while $L/\delta_{I,eq}$ spans a relatively large range from 200 to 800, the deflections of more than 50% of all the optimal sustainable hybrid beams

are observed to be between $L/200$ and $L/300$, close to the serviceability limit, which demonstrates that serviceability considerations generally become more critical in the hybrid design scenario.

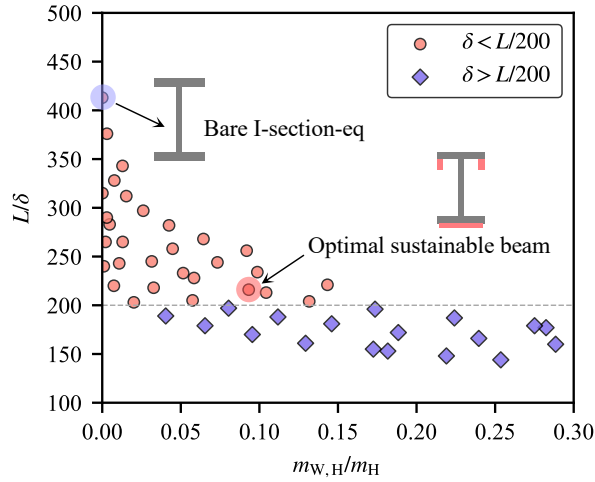


Figure 18: Span-to-deflection ratios of the designed beams in the same design case as shown in Fig. 17.

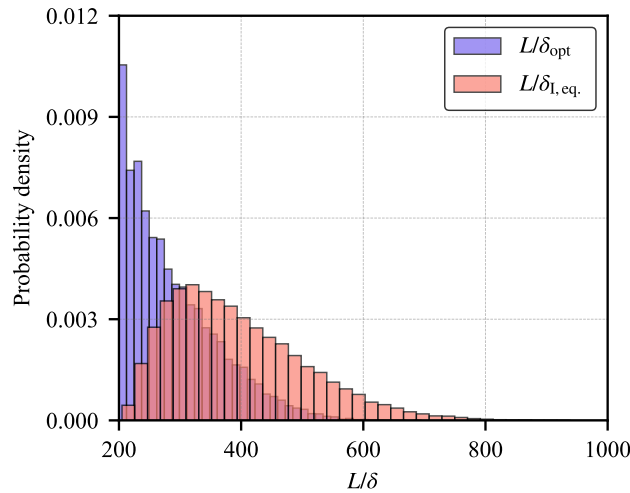


Figure 19: Probability distributions of $L/\delta_{l,eq}$ and of L/δ_{opt} for all design cases.

In Figs. 20 (a) and (b), the optimal sustainable design in all the design cases corresponding to the ER110-S355-3PB and ER70-S355-3PB scenarios are presented respectively, where the hybrid rates and normalised GWP – denoted as GWP^* – of the optimal sustainable beams, and the probability distribution of GWP^* , are shown. A colour-scale is also included in Fig. 20 to represent the span-to-deflection ratio of the bare I-section-eq in each design case. Note that the colour-scale is logarithmic.

Overall, it can be observed from Fig. 20 that greater reductions in GWP can be achieved in the design cases where relatively high hybrid rates are attainable; these cases in general correspond to relatively high values of $L/\delta_{l,eq}$ (i.e., high redundancy in flexural stiffness of the bare I-section-eq). Conversely, in those cases with a low value of $L/\delta_{l,eq}$, typically resulting from a high span-to-depth ratio and/or a large live load (i.e., a high α value), a high hybrid rate was not attainable in the hybrid design due to excessive deflection, see the upper left corner of Figs. 20 (a) and (b). This prevents the hybrid design from achieving higher mass reductions and, consequently, greater reduction in GWP. Additionally, in some of these large-deflection cases, the bare I-section-eq itself has the lowest GWP (i.e. $GWP^* = 1$), and is therefore the optimal sustainable beam, as reflected in the upper corner of the probability histogram. Hence, it

Table 10

Descriptive statistics of GWP* for optimal sustainable designs.

Loading condition	ER110-S355				ER70-S355			
	Mean	Min	CoV	Non-hybrid %	Mean	Min	CoV	Non-hybrid %
3PB	0.793	0.611	0.076	1.04%	0.823	0.660	0.062	1.00%
4PB	0.915	0.757	0.052	10.60%	0.943	0.813	0.04	14.44%
UDL	0.897	0.734	0.056	9.32%	0.921	0.786	0.045	7.44%
3PB+UDL	0.845	0.619	0.076	4.13%	0.871	0.664	0.063	4.09%
4PB+UDL	0.907	0.743	0.052	9.12%	0.933	0.796	0.043	11.64%
All	0.862	0.611	0.081	5.82%	0.887	0.660	0.070	6.36%

can be concluded that the hybrid design and manufacturing strategy for steel beams is more effective in reducing GWP when higher redundancy in flexural stiffness is present.

The descriptive statistics of the optimal sustainable beams are summarised in Table 10 for all design scenarios. The percentages of the design cases where the bare I-section-eq becomes optimal in GWP are also provided, denoted as the non-hybrid percentage. Overall, average reductions in GWP of 11% and 14% are shown to be achievable through the hybrid design and manufacturing strategy, for the ER70-S355 and ER110-S355 hybrid beams respectively, while the maximum achieved reductions in GWP were 34% and 39%, respectively. Note that, for bare I-sections in lower steel grades, the achievable reductions in GWP are even greater. For example, for S275 steel beams, it was found that average reductions in GWP of between 17% and 22% were achievable for ER70-S275 and ER110-S275 hybrid beams respectively, while the maximum achieved reductions in GWP were 41% and 45%, respectively. This positions the hybrid strategy well for retrofitting applications, as well as strengthening for re-use.

From Table 10, it can be observed that the reductions in GWP are dependent on the loading conditions, with the 3PB cases exhibiting greater GWP reductions than the 4PB and the UDL cases. This trend can be attributed to the uniformity of the corresponding bending moment diagrams. A uniformity factor, ξ , is defined as the ratio of the area of the bending moment diagram to that of the enveloping rectangle; thus, accordingly, $\xi = 1/2$ for the 3PB cases, and $\xi = 2/3$ for the 4PB, UDL and 4PB+UDL cases. For a prismatic I-section beam, the material utilisation is less efficient when subjected to a bending moment diagram with a low ξ , such as in the 3PB condition, where relatively low stress levels are present in the structural regions away from the mid-span, resulting in material redundancy. The hybrid design and optimisation approach addresses this redundancy, and is therefore expected to be more effective under the loading conditions with low ξ . For the 3PB+UDL loading condition, the uniformity factor ξ varies with respect to the parameter, β , thus:

$$\xi = \frac{1}{2} + \frac{\beta}{6}, \quad (5)$$

where β varies from 0 (3PB) to 1 (UDL). In Fig. 21, the variation of GWP* with respect to ξ is plotted for the optimal sustainable ER110-S355 hybrid beams subjected to 3PB+UDL, where it can be observed that GWP* increases monotonically with increasing ξ , as expected.

5.4. Discussion

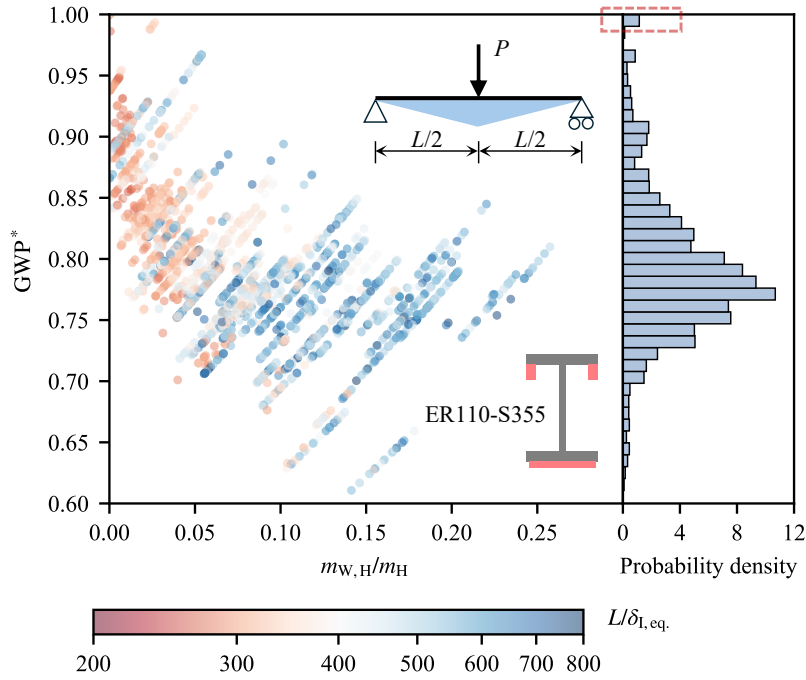
Having demonstrated the capability of the hybrid manufacturing strategy to reduce the GWP of steel beams, it should be emphasised that other midpoint impact categories should not be overlooked in decision-making regarding the application of such manufacturing routes. Although the present work primarily focuses on the embodied carbon and GWP reduction, reflecting the urgent need for decarbonisation in the construction sector, the unit-mass LCA results indicate that broader environmental trade-offs may arise. In particular, while high-strength DED-arc steels offer structural advantages and may enable larger material savings and GWP reductions at the member level, the unit-mass LCA results presented in Section 3.6 show that the ER110S-G and ER120S-G DED-arc steels have

substantially higher impacts than S355 hot-rolled steel in several toxicity- and ecotoxicity-related categories. These increases are mainly associated with the alloying additions required for high-strength steel production, particularly manganese and molybdenum, which contribute notably to human toxicity and freshwater ecotoxicity, respectively. Therefore, the environmental performance of hybrid DED-arc-hot-rolled beams should be interpreted as a multi-criteria decision problem, rather than a GWP-only assessment. High-strength DED-arc additions may be beneficial where decarbonisation is the primary design objective; however, for applications or regulatory contexts in which toxicity, ecotoxicity or water-related impacts are critical, lower-alloy DED-arc steels, reduced alloying contents, alternative wire production routes or conventional hot-rolled solutions may be more appropriate. These trade-offs should therefore be considered when selecting the DED-arc steel grade and the corresponding hybrid beam design.

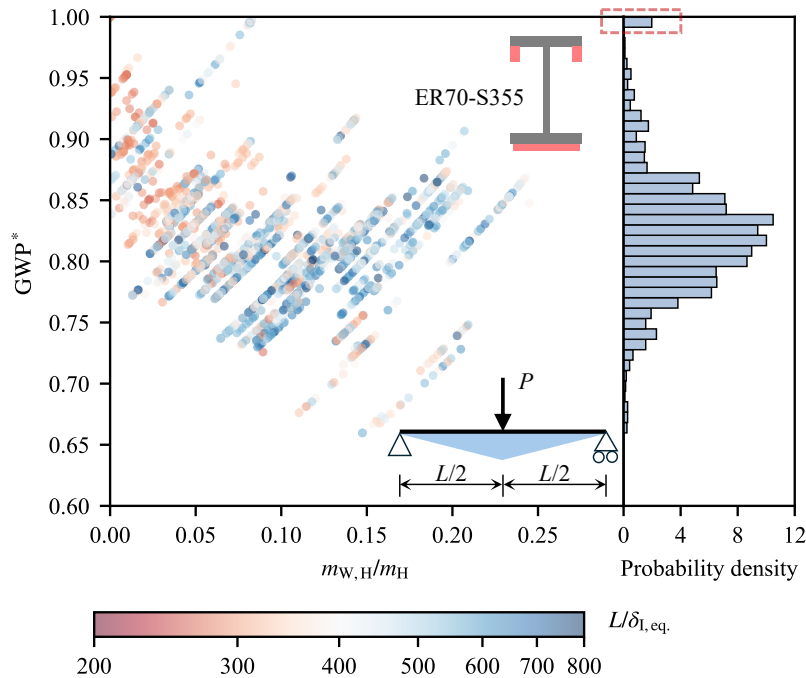
It should be noted that the present work considers flexure-dominated design cases only, which is appropriate since steel beams in construction are most commonly governed by flexural resistance, and hence the results are representative of a broad range of practical beam design scenarios. In general, in flexure-dominated design cases, the hybrid manufacturing strategy is more effective in reducing embodied carbon when the loading condition has a lower uniformity factor. However, for design cases in which the steel beam is governed by other limit states, such as deflection, shear resistance or instability such as lateral-torsional buckling, different design strategies may be required, and their associated environmental implications are beyond the scope of the present study and should be investigated in future work.

The environmental performance of hybrid DED-arc-hot-rolled steel beams may also evolve as the DED-arc additive manufacturing technology matures. Recent prospective LCA work on future DED-arc deposition processes has indicated that technological developments, including plasma-based systems, multi-axis deposition strategies and industrial-scale process optimisation could substantially reduce the environmental impacts of DED-arc manufacturing compared with current systems [62]. For hybrid steel construction, such improvements would be expected to reduce the unit-mass environmental burden of the DED-arc additions, particularly of the high-strength DED-arc steels, and therefore lower the material-saving threshold required for the hybrid beams to achieve net GWP reductions relative to conventional hot-rolled counterparts. Multi-axis deposition, higher deposition efficiency and improved process productivity could reduce wire losses, electricity and shielding gas demand and production time.

Finally, it should be mentioned that the practical implementation of the hybrid manufacturing strategy at industrial scale would require further development and qualification. Some key issues include deposition productivity, dimensional accuracy, residual stress and distortion control, reliability and quality control of the deposited material and compatibility with existing steel fabrication routes and supply-chain workflows. These aspects are not directly reflected in the cradle-to-gate LCA presented in this study, but may influence the economic feasibility, production scalability and real-world uptake of the proposed hybrid manufacturing strategy.



(a)



(b)

Figure 20: Optimal sustainable designs for two typical design scenarios: (a) 3PB & ER110S-G DED-arc steel and (b) 3PB & ER70S-2 DED-arc steel.

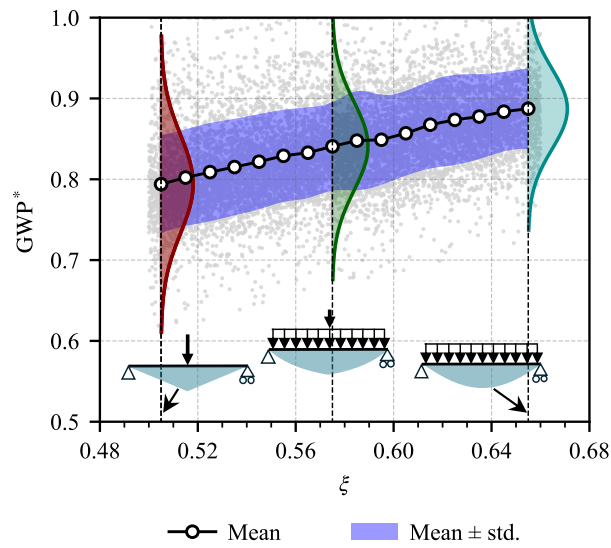


Figure 21: Variation of GWP^* with respect to ξ for the optimal sustainable ER110-S355 hybrid beams subjected to 3PB+UDL.

6. Conclusions

The structural and environmental benefits of combining metal 3D printing with conventional steelwork, referred to as hybrid construction, has been explored in this paper. A cradle-to-gate life cycle assessment (LCA) of the hybrid DED-arc-hot-rolled I-section beams using the OpenLCA package [36] and the *Ecoinvent 3.8* database [37] has been conducted. The environmental impacts of previously tested hybrid beams [18, 19] were evaluated using the ReCiPe midpoint method [47], where reductions in the global warming potential (GWP) up to 19% were demonstrated. A comprehensive parametric study covering a wide range of loading conditions, I-section geometries and hybrid rates was subsequently conducted to assess the overall potential of this novel hybrid DED-arc-hot-rolled manufacturing strategy in reducing the carbon footprint of steel structures. The results showed that average reductions in GWP of 11% and 14% were achievable for normal (ER70-S) and high (ER110S-G) strength steel additions, and maximum reductions of almost 40%, can be achieved for different loading conditions, compared with conventional hot-rolled S355 bare steel beams. For S275 bare steel beams, which are particularly relevant in retrofitting and re-use scenarios, even greater savings in embodied carbon, up to 45%, can be achieved. These findings highlight the strong promise of hybrid manufacturing as a viable pathway towards more sustainable steel construction in future.

Acknowledgments

The authors would like to thank to Imperial College London for the financial support provided through the Skempton scholarship from the Department of Civil and Environmental Engineering for the lead author.

Appendices

A. Supplementary material for the unit-mass analysis

In the current appendix, supplementary material for the unit-mass analysis, as presented in Section 3, is provided, including the input/output flows and reference processes used for modelling the life cycle inventory. Some typical impact assessment results are also presented.

Tables A1–A3 list the typical chemical composition of the carbon steel used for producing the three grades of welding wire; the corresponding input flows and reference processes used to model each of the alloying elements are also given. To ensure mass conservation, the Fe content within the ferroalloys (see Tables A1–A3) was assumed to enter the final steel and thus was correspondingly subtracted from the amount of the unalloyed steel input. For ferrochromium (68% Cr) and ferromanganese (74.5% Mn), where the Fe contents are not explicitly specified in the *Ecoinvent 3.8* database [37], conservative values of 22% and 15.5% respectively, were adopted, with the remaining 10% being other residual alloying elements that leaves the system boundary of the LCA. For ferronickel (25% nickel) and ferrosilicon (75% silicon), the residual fractions were considered negligible, and hence the Fe content was assumed to be 75% and 25%, respectively.

The reference processes used to model the electricity production for the DED-arc operations are listed in Table A4, together with the amounts of electricity consumed per depositing 1 kg of ER70S-2, ER110S-G and ER120S-G DED-arc steel. Note that for the ‘Import’ category, it was assumed that three equal portions of electricity are imported from France, Ireland and Netherlands to the UK, as corresponding reference data are available in the *Ecoinvent 3.8* database [37].

Table A5 summarises the mass of the consumed material(s) at each production stage for finally producing 1 kg of S355 hot-rolled I-section or DED-arc steel, adopting the material utilization rates presented in Section 3.4. In Tables A6–A9, the contributions of the individual production stages to the overall environmental impacts associated with the unit-mass productions are given for the four steel types in detail, across some selected impact categories covering climate change, water depletion and pollution and human health.

Table A1: Typical chemical composition, adopted reference flows and processes from *Ecoinvent 3.8* database, and corresponding weights of the input flows for the ER70S-2 steel production. (* indicates assumed percentage)

Components	Composition (wt. %)	Reference flow from <i>Ecoinvent 3.8</i>		Reference process from <i>Ecoinvent 3.8</i>
		Flow name	Content (by weight)	Flow weight kg per 1 kg produced steel
Mn	1.10	Ferromanganese	74.5% Mn, 15.5%* Fe, 10%* other	0.0148
Si	0.55	Ferrosilicon	75% Si, 25%* Fe	0.0073
Al	0.11	Aluminium ingot	100%* Al	0.0011
Zr	0.07	Ferronickel	50% Zr	0.0014
Fe + other	98.17	Steel, unalloyed	–	0.9769

Table A2: Typical chemical composition, adopted reference flows and processes from *Ecoinvent 3.8* database, and corresponding weights of the input flows for the ERI10S-G steel production. (* indicates assumed percentage)

Components	Composition (wt. %)	Reference flow from <i>Ecoinvent 3.8</i>		Reference process from <i>Ecoinvent 3.8</i>
		Flow name	Content (by weight) kg per 1 kg produced steel	
Mn	1.70	Ferromanganese	74.5% Mn, 15.5%* Fe, 10%* other	market for ferromanganese, high-coal, 74.5% Mn
Si	0.70	Ferrosilicon	75% Si, 25%* Fe	market for ferrosilicon
Cr	0.30	Ferrochromium	68% Cr, 22%* Fe, 10%* other	market for ferrochromium, high-carbon, 68% Cr
Ni	1.85	Ferronickel	25% Ni, 75%* Fe	market for ferronickel
Mo	0.60	Molybdenum	100%* Mo	market for molybdenum
Fe + other	94.85	Steel, unalloyed	–	market for steel, unalloyed

Table A3: Typical chemical composition, adopted reference flows and processes from *Ecoinvent 3.8* database, and corresponding weights of the input flows for the ERI20S-G steel production. (* indicates assumed percentage)

Components	Composition (wt. %)	Reference flow from <i>Ecoinvent 3.8</i>		Reference process from <i>Ecoinvent 3.8</i>
		Flow name	Content (by weight) kg per 1 kg produced steel	
Mn	1.80	Ferromanganese	74.5% Mn, 15.5%* Fe, 10%* other	market for ferromanganese, high-coal, 74.5% Mn
Si	0.80	Ferrosilicon	75% Si, 25%* Fe	market for ferrosilicon
Cr	0.35	Ferrochromium	68% Cr, 22%* Fe, 10%* other	market for ferrochromium, high-carbon, 68% Cr
Ni	2.25	Ferronickel	25% Ni, 75%* Fe	market for ferronickel
Mo	0.60	Molybdenum	100%* Mo	market for molybdenum
Fe + other	94.20	Steel, unalloyed	–	market for steel, unalloyed

Table A4: Electricity generation/production and transmission per depositing 1 kg DED-arc steel (unit: kWh).

Electricity production	Reference process	ER70S-2	ER110S-G & ER120S-G
Gas	<i>electricity production, natural gas, conventional power plant - GB</i>	0.405	0.456
Wind	<i>electricity production, wind, >3MW turbine, onshore - GB</i>	0.462	0.520
Nuclear	<i>electricity production, nuclear, pressure water reactor - GB</i>	0.216	0.243
Biomass	<i>electricity production, wood, future</i>	0.105	0.118
Coal	<i>electricity production, hard coal - GB</i>	0.009	0.010
Solar	<i>electricity production, solar thermal parabolic trough, 50 MW</i>	0.077	0.087
Imports	<i>1/3 from electricity, high voltage, import from NL - GB</i>	0.217	0.244
	<i>1/3 from electricity, high voltage, import from FR - GB</i>		
	<i>1/3 from electricity, high voltage, import from IE - GB</i>		
Hydro	<i>electricity production, hydro, run-of-river - GB</i>	0.031	0.035
Storage	<i>electricity production, hydro, pumped storage - GB</i>	0.018	0.021
Sum		1.540 kWh	1.734 kWh

Table A5: Material consumption (input → output) at each production stage per producing 1 kg hot-rolled S355 I-section or DED-arc steel (unit: kg).

Stage	Input → output	Production of hot-rolled steel	Production of ER70S-2 DED-arc steel	Production of ER110S-G or ER120S-G DED-arc steel
Carbon steel production	Raw materials → carbon steel	1.053 → 1.053	1.272 → 1.272	1.218 → 1.218
Hot-rolling	Carbon steel → hot-rolled I-section/rods	1.053 → 1.000	1.272 → 1.208	1.218 → 1.158
Wire drawing	Rods → welding wire	–	1.208 → 1.087	1.158 → 1.042
DED-arc	Welding wire → DED-arc steel	–	1.087 → 1.000	1.042 → 1.000
Protective painting	Hot-rolled/DED-arc steel → product	1.000 → 1.000	1.000 → 1.000	1.000 → 1.000
Final steel product		1.000	1.000	1.000

Table A6: Contributions of individual production stage to the overall environmental impact for the production of 1 kg S355 hot-rolled I-section.

S355 hot-rolled steel	Global warming		Water consumption		Human carcinogenic toxicity		Freshwater ecotoxicity	
	kg CO ₂ eq	Contribution	m ³	Contribution	kg 1,4-DCB	Contribution	kg 1,4-DCB	Contribution
Steel production	Low-alloyed steel							
	1.957	78.50%	0.017	55.47%	2.843	94.22%	0.176	88.36%
Hot-rolling	0.270	10.84%	0.008	27.85%	0.163	5.40%	0.012	5.99%
Protective painting	0.266	10.66%	0.005	16.68%	0.012	0.38%	0.011	5.65%
Sum	2.493	100.00%	0.030	100.00%	3.017	100.00%	0.199	100.00%

Table A7: Contributions of individual production stage to the overall environmental impact for the production of 1 kg ER70S-2 DED-arc steel.

ER70S-2 DED-arc steel		Global warming		Water consumption		Human carcinogenic toxicity		Freshwater ecotoxicity	
		kg CO ₂ eq	Contribution	m ³	Contribution	kg 1,4-DCB	Contribution	kg 1,4-DCB	Contribution
Steel production	Unalloyed steel	2.016	48.09%	0.012	13.48%	1.010	34.59%	0.121	48.70%
	Additional alloying elements	0.134	3.21%	0.001	1.16%	1.341	45.94%	0.024	9.62%
Hot-rolling		0.294	7.01%	0.009	10.44%	0.177	6.06%	0.013	5.20%
Wire drawing		0.397	9.48%	0.018	19.99%	0.315	10.80%	0.022	8.97%
DED-arc	Shielding gas	0.758	18.08%	0.041	47.05%	0.050	1.71%	0.033	13.08%
	Electricity	0.327	7.80%	0.002	2.13%	0.015	0.50%	0.025	9.92%
Protective painting		0.266	6.34%	0.005	5.75%	0.012	0.39%	0.011	4.50%
Sum		4.192	100.00%	0.088	100.00%	2.920	100.00%	0.249	100.00%

Table A8: Contributions of individual production stage to the overall environmental impact for the production of 1 kg ER110S-G DED-arc steel.

ER110S-G DED-arc steel		Global warming		Water consumption		Human carcinogenic toxicity		Freshwater ecotoxicity	
		kg CO ₂ eq	Contribution	m ³	Contribution	kg 1,4-DCB	Contribution	kg 1,4-DCB	Contribution
Steel production	Unalloyed steel	1.752	34.19%	0.010	9.30%	0.878	24.89%	0.105	9.70%
	Additional alloying elements	1.004	19.59%	0.009	8.57%	2.079	58.95%	0.863	79.37%
Hot-rolling		0.282	5.49%	0.009	7.93%	0.170	4.81%	0.012	1.14%
Wire drawing		0.381	7.43%	0.017	15.20%	0.302	8.57%	0.021	1.97%
DED-arc	Shielding gas	1.066	20.80%	0.058	52.52%	0.070	2.00%	0.046	4.22%
	Electricity	0.375	7.32%	0.002	1.92%	0.016	0.46%	0.028	2.57%
Protective painting		0.266	5.19%	0.005	4.56%	0.012	0.33%	0.011	1.03%
Sum		5.126	100.00%	0.111	100.00%	3.527	100.00%	1.087	100.00%

Table A9: Contributions of individual production stage to the overall environmental impact for the production of 1 kg ER120S-G DED-arc steel.

ER120S-G DED-arc steel		Global warming		Water consumption		Human carcinogenic toxicity		Freshwater ecotoxicity	
		kg CO ₂ eq	Contribution	m ³	Contribution	kg 1,4-DCB	Contribution	kg 1,4-DCB	Contribution
Steel production	Unalloyed steel	1.704	32.54%	0.010	8.97%	0.854	23.58%	0.102	9.34%
	Additional alloying elements	1.171	22.36%	0.011	9.54%	2.200	60.76%	0.874	79.84%
Hot-rolling		0.281	5.37%	0.009	7.87%	0.169	4.68%	0.012	1.13%
Wire drawing		0.380	7.26%	0.017	15.06%	0.302	8.33%	0.021	1.95%
DED-arc	Shielding gas	1.067	20.37%	0.058	52.15%	0.070	1.95%	0.046	4.19%
	Electricity	0.368	7.03%	0.002	1.88%	0.014	0.38%	0.028	2.53%
Protective painting		0.266	5.08%	0.005	4.53%	0.012	0.32%	0.011	1.02%
Sum		5.237	100.00%	0.111	100.00%	3.621	100.00%	1.095	100.00%

CRedit authorship contribution statement

Jiachi Yang: Data curation, Writing – Original draft preparation, Visualization, Investigation, Software, Validation. **Kyvelou Pinelopi:** Conceptualization, Methodology, Writing – Reviewing and Editing, Supervision. **M. Ahmer Wadee:** Conceptualization, Methodology, Writing – Reviewing and Editing, Supervision. **Leroy Gardner:** Conceptualization, Methodology, Writing – Reviewing and Editing, Supervision.

References

- [1] United Nations Environment Programme. *Global Status Report for Buildings and Construction 2024/2025*. United Nations Environment Programme, 2025.
- [2] United Nations Framework Convention on Climate Change. Paris agreement. Adopted at the 21st Conference of the Parties (COP21), Paris, 2015. URL <https://unfccc.int/process-and-meetings/the-paris-agreement>. Accessed: 2025-11-20.
- [3] Intergovernmental Panel on Climate Change. Global warming of 1.5 °C. an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, 2018. URL <https://www.ipcc.ch/sr15/>. Accessed: 2025-11-20.
- [4] International Energy Agency. Net zero by 2050: A roadmap for the global energy sector, 2021. URL <https://www.iea.org/reports/net-zero-by-2050>. Accessed: 2025-11-20.
- [5] European Commission. 2050 long-term strategy: A climate-neutral europe by 2050. EU Climate Action web publication, 2020. URL https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en. Accessed: 2025-11-20.
- [6] M. Armstrong, H. Mehrabi, and N. Naveed. An overview of modern metal additive manufacturing technology. *Journal of Manufacturing Processes*, 84:1001–1029, 2022.
- [7] L. Gardner. Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook. *Structures*, 47:2178–2193, 2023.
- [8] B. Weber, X. Meng, R. Zhang, M. Nitawaki, T. Sagawa, and L. Gardner. Tensile behaviour of waam high strength steel material and members. *Materials & Design*, 237:112517, 2024.
- [9] A. Spinasa, B. Weber, X. Meng, R. Zhang, M. Nitawaki, and L. Gardner. Influence of process parameters on the physical and material properties of waam steels. *Construction and Building Materials*, 479:141078, 2025.
- [10] C. Huang, L. Li, N. Pichler, E. Ghafoori, L. Susmel, and L. Gardner. Fatigue testing and analysis of steel plates manufactured by wire-arc directed energy deposition. *Additive Manufacturing*, 73:103696, 2023.
- [11] W. Zuo, M. T. Chen, O. Zhao, and L. Gardner. Testing of wire arc additively manufactured duplex stainless steel double-lap shear bolted connections. *Journal of Structural Engineering, ASCE*, 151(2):04024205, 2025.
- [12] X. Guo, P. Kyvelou, J. Ye, L. Teh, and L. Gardner. Experimental investigation of wire arc additively manufactured steel single-lap shear bolted connections. *Thin-Walled Structures*, 181:110029, 2022.
- [13] B. Weber, X. Meng, and L. Gardner. Optimised and 3d printed steel garden bridge: from design to experimental verification. *Automation in Construction*, 181:106638, 2026.
- [14] S. Evans, J. Wang, J. Pan, and F. Xu. Experimental study of wire arc additively manufactured steel sections stiffened by sinusoidal waves. *Structures*, 65:106641, 2024.
- [15] X. Meng, B. Weber, M. Nitawaki, and L. Gardner. Optimisation and testing of wire arc additively manufactured steel stub columns. *Thin-Walled Structures*, 189:110857, 2023.
- [16] P. Kyvelou, A. Spinasa, and L. Gardner. Testing and analysis of optimized wire arc additively manufactured steel trusses. *Journal of Structural Engineering*, 150(3):04024008, 2024.
- [17] L. Gardner, J. Li, X. Meng, C. Huang, and P. Kyvelou. I-section steel columns strengthened by wire arc additive manufacturing – concept and experiments. *Engineering Structures*, 306:117763, 2024.
- [18] J. Yang, M. A. Wadee, and L. Gardner. Strengthening of hot-rolled S355 steel I-section beams using WAAM high strength steel. *Thin-Walled Structures*, 215:113437, 2025.
- [19] J. Yang, M. A. Wadee, and L. Gardner. Strengthening of steel I-section beams by wire arc additive manufacturing – concept and experiments. *Engineering Structures*, 322:119113, 2025.
- [20] M. H. Baqershahi, C. Ayas, and E. Ghafoori. Design optimisation for hybrid metal additive manufacturing for sustainable construction. *Engineering Structures*, 301:117355, 2024.
- [21] X. Meng and L. Gardner. Hybrid construction featuring wire arc additive manufacturing: review, concepts, challenges and opportunities. *Engineering Structures*, 326:119337, 2025.
- [22] MX3D. Architecture & construction, 2021. URL <https://mx3d.com/industries/architecture-construction>. Accessed: 2025-11-19.
- [23] ISO 14040. *Environmental management — Life cycle assessment — Principles and framework*. International Organization for Standardization, Geneva, Switzerland, 2006.
- [24] ISO 14044. *Environmental management — Life cycle assessment — Requirements and guidelines*. International Organization for Standardization, Geneva, Switzerland, 2006.
- [25] J. Faludi, C. Bayley, S. Bhogal, and M. Iribarne. Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, 21(1):14–33, 2015.

- [26] P. C. Priarone, G. Campatelli, A. R. Catalano, and F. Baffa. Life-cycle energy and carbon saving potential of wire arc additive manufacturing for the repair of mold inserts. *CIRP Journal of Manufacturing Science and Technology*, 35:943–958, 2021.
- [27] M. Kafara, M. Süchting, J. Kemnitzer, H. Westermann, and R. Steinhilper. Comparative life cycle assessment of conventional and additive manufacturing in mold core making for CFRP production. *Procedia Manufacturing*, 8:223–230, 2017.
- [28] H. Paris, H. Mokhtarian, E. Coatanéa, M. Museau, and I. F. Ituarte. Comparative environmental impacts of additive and subtractive manufacturing technologies. *CIRP Annals – Manufacturing Technology*, 65(1):29–32, 2016.
- [29] J. R. Gouveia, S. M. Pinto, S. Campos, A. Ramos, and A. Fonseca. Life cycle assessment and cost analysis of additive manufacturing repair processes in the mold industry. *Sustainability*, 14(4):2105, 2022.
- [30] S. Kokare, J. P. Oliveira, and R. Godina. Life cycle assessment of additive manufacturing processes: A review. *Journal of Manufacturing Systems*, 68:536–559, 2023.
- [31] A. C. M. Bekker and J. C. Verlinden. Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel. *Journal of Cleaner Production*, 177:438–447, 2018.
- [32] L. Arrè, E. Pagone, V. Laghi, F. Martina, and M. Palermo. Comparative life-cycle assessment of novel steel section design with wire arc additive manufacturing. In A. Lazou, C. Meskers, E. Olivetti, F. Diaz, and M. Gökelma, editors, *REWAS 2025*, pages 179–189, Cham, 2025. Springer Nature Switzerland.
- [33] I. H. Shah, N. Hadjipantelis, L. Walter, R. J. Myers, and L. Gardner. Environmental life cycle assessment of wire arc additively manufactured steel structural components. *Journal of Cleaner Production*, 389:136071, 2023.
- [34] EN 1993-1-1. *Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings*. European Committee for Standardization, Brussels, 2022.
- [35] M. Kucukler, L. Gardner, and L. Macorini. Lateral-torsional buckling assessment of steel beams through a stiffness reduction method. *Journal of Constructional Steel Research*, 109:87–100, 2015.
- [36] GreenDelta GmbH. *openLCA 2.0 [software]*. Berlin, Germany, 2023. URL <https://www.openlca.org/>.
- [37] Ecoinvent. *ecoinvent database version 3.8*. Zurich, Switzerland, 2024. URL <https://www.ecoinvent.org/>.
- [38] A. Ghosh and A. Chatterjee. *Ironmaking and Steelmaking: Theory and Practice*. PHI Learning, 2008.
- [39] R. J. Fruehan, editor. *The Making, Shaping and Treating of Steel: Steelmaking and Refining*. AISE Steel Foundation, 11 edition, 1998.
- [40] ISO. Iso 12944-5:2019 — paints and varnishes — corrosion protection of steel structures by protective paint systems — part 5: Protective paint systems, 2019. ISO standard.
- [41] R. N. Wright. *Wire Technology: Process Engineering and Metallurgy*. Woodhead Publishing (Elsevier), 2011.
- [42] L. F. Jeffus. *Welding: Principles and Applications*. Thomson/Delmar Learning, 2004.
- [43] Howard B. Cary and Scott C. Helzer. *Modern Welding Technology*. Pearson Education, Upper Saddle River, NJ, 6th edition, 2005.
- [44] National Energy System Operator (NESO). Britain's electricity explained: 2024 review, 2024. URL <https://www.neso.energy/news/britains-electricity-explained-2024-review>. Accessed: 19 October 2025.
- [45] Granta Design. Ansys granta edupack: Materials information management. *Grant a Des*, 2019.
- [46] ASM International, editor. *ASM Handbook, Volume 6: Welding, Brazing, and Soldering*. ASM International, Materials Park, OH, 10th edition, 1993.
- [47] M. A. J. Huijbregts, Z. J. N. Steinmann, P. M. F. Elshout, G. Stam, F. Verones, M. Vieira, M. Zijp, A. Hollander, and R. Van Zelm. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, 22: 138–147, 2017.
- [48] M. Mistry, J. Gediga, and S. Boonzaier. Life cycle assessment of nickel products. *The International Journal of Life Cycle Assessment*, 21(11): 1559–1572, 2016.
- [49] Vovia W. Jannick S. and Marie N. Nickel for the energy transition – a developmental perspective, 2022.
- [50] U.S. Environmental Protection Agency. *National Emission Standards for Hazardous Air Pollutants for Ferroalloys Production: Ferromanganese and Silicomanganese*, 1999.
- [51] M. G. Macklin, C. J. Thomas, A. Mudbhakal, P. A. Brewer, K. A. Hudson-Edwards, J. Lewin, P. Scussolini, D. Eilander, A. Lechner, J. Owen, G. Bird, D. Kemp, and K. R. Mangalaa. Impacts of metal mining on river systems: a global assessment. *Science*, 381:1345–1350, 2023.
- [52] AWS A5.28 ER110S-G: *Gas Shielded Solid Welding Wire*. Xiang Welding Industrial Co. Ltd., 2020. URL https://www.xiangind.com/aws_er110s-g. Manufacturer wire certificate/specification sheet, accessed 21 June 2026.
- [53] ER110S-G: *TIG Rod, Low Alloy Steel*. Lincoln Electric, 2025. Manufacturer wire certificate/specification sheet.
- [54] ER 110 SG: *High Strength MAG Wire & TIG Rod*. Gedik Welding, n.d. URL <https://www.gedikwelding.com>. Manufacturer wire certificate/specification sheet.
- [55] GM 110S-G: *Solid Wire for Gas-Shielded Metal Arc Welding*. GEE Limited, n.d. URL <https://www.geelimited.com>. Manufacturer wire certificate/specification sheet.
- [56] ER 110S-G: *Low Alloy TIG/GTAW Technical Data Sheet*. Wilkinson Star, n.d. URL <https://www.wilkinsonstar247.com>. Manufacturer wire certificate/specification sheet.
- [57] TIGFIL 110S-G: *GTAW Low Alloy Steel*. Ador Welding Limited, n.d. URL <https://www.adorwelding.com>. Manufacturer wire certificate/specification sheet.
- [58] Steel Construction Institute. *Steel Building Design: Design Data*. SCI Publication P363, Ascot, UK, 2015.
- [59] O. Zhao, B. Rossi, L. Gardner, and B. Young. Behaviour of structural stainless steel cross-sections under combined loading – part ii: Numerical modelling and design approach. *ngineering Structures*, 89:247–259, 2015.
- [60] L. Gardner, F. Wang, and A. Liew. Influence of strain hardening on the behavior and design of steel structures. *International Journal of Structural Stability and Dynamics*, 11(5):855–875, 2011.
- [61] EN 1990. *Eurocode – Basis of structural design*. European Committee for Standardization, Brussels, 2005.

- [62] Christian Spreafico, Samruddha Kokare, and Radu Godina. Prospective life cycle assessment of future wire arc additive manufacturing deposition process for large-scale steel parts. *Environmental Impact Assessment Review*, 2026.